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EVALUATION OF DIESEL SMOKE INSPECTION PROCEDURES AND SMOKEMETERS

John O. Storment, et al

Southwest Research Institute

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by

John O. Storment
Karl J. Springer

FINAL REPORT

Prepared for
Environmental Protection Agency
Air Pollution Control Office
Mobile Source Pollution Control Program
Division of Emission Control Technology
Contract EHS 70-109

July 1972

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Various vehicle smoke test procedures, smokemeters, and smoke opacity measurement techniques were evaluated by comparison to well known standards. The test procedures were compared to a chassis-dynamometer version of the Federal smoke compliance test. The performance of six commercial smokemeters was compared to that of the standard PHS smokemeter. Also, end-of-line and inline opacity measurements were evaluated by using an inline version of the PHS smokemeter. The smoke test procedures investigated showed varying degrees of correlation with the simulated Federal smoke test, but no one procedure produced data that correlated with the Federal test in every test instance. Inline and end-of-line opacity readings were obtained simultaneously during transient and steady-state engine conditions. The data from these tests showed that the inline and end-of-line instruments registered similar opacity, although the inline smokemeter read lower than the end-of-stack in most cases. Other investigations were also conducted: Two enlarged versions of the PHS smokemeter were tested and showed good agreement with the standard unit. Three standard PHS instruments were used in a series of repetitive smoke tests and exhibited excellent agreement.

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July 1972

Approved:
John M. Clark
John M. Clark, Jr., Director
Department of Automotive Research

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ABSTRACT

Various vehicle smoke test procedures, smokemeters, and smoke opacity measurement techniques were evaluated by comparison to well-known standards. The test procedures, which were designed as brief inspections of smoke from diesel-powered trucks and buses, were compared to a chassis-dynamometer version of the Federal smoke compliance test. The performance of six commercial smokemeters was compared to that of the standard PHS smokemeter. Also, end-of-line and inline opacity measurements were evaluated by using an inline version of the PHS smokemeter. This inline instrument was developed and constructed at Southwest Research Institute as part of this project.

The smoke test procedures investigated showed varying degrees of correlation with the simulated Federal smoke test, but no one procedure produced data that correlated with the Federal test in every test instance. Two commercially-available smokemeters performed well and correlated with the standard PHS instrument in a number of tests. However, certain combinations of test procedure and engine type were found for which these two smokemeters did not correlate well with the PHS unit. The inline smokemeter developed by SwRI is of the same general design as the PHS end-of-line smokemeter and uses most of the standard PHS components. Inline and end-of-line opacity readings were obtained simultaneously during transient and steady-state engine conditions. The data from these tests showed that the inline and end-of-line instruments registered similar opacity, although the inline smokemeter read lower than the end-of-stack in most cases.

Several other aspects of diesel smoke opacity measurement were also investigated in the course of this project. Two enlarged versions of the PHS smokemeter were tested and showed good agreement with the standard unit. Three standard PHS instruments were used in a series of repetitive smoke tests and exhibited excellent agreement. This latter series of tests also served as verification of the effectiveness of the Beere-Lambert law in correcting indicated smoke opacity for small-diameter exhaust stacks.

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I. INTRODUCTION

In 1966 the original prototype of the U. S. Public Health Service full-flow, light-extinction smokemeter was sent to Southwest Research Institute that several copies of the instrument could be made. This was the first smokemeter designed to measure the density of diesel smoke by the principle of the human eye, i.e., light obscuration by the smoke itself. Early tests at SwRI using the PHS instrument marked the beginning of a long-range Environmental Protection Agency (EPA) study(1-4)* involving diesel-powered trucks and buses, chassis dynamometers, and test procedures. One of the principal objectives of this study was to measure and characterize the smoke emissions of diesel engines under both transient and steady-state operation. The PHS smokemeter was used almost exclusively in this study. In the years since its inception, the PHS instrument has been improved(5,6), but the basic concept has remained unchanged.

In 1968, the Federal Government established standards for smoke output from 1970 and later model diesel engines used in vehicles above 6,000 lbs. GVW(7). Compliance with these standards was (and is) certified by subjecting a typical production engine, representative of a certain class or family of engines, to the Federal smoke compliance test(7,8). The PHS smokemeter is specified for use in all compliance tests. Hence, the Federal smoke test procedure and the PHS smokemeter have become standards in the measurement of smoke opacity from automotive-type diesel engines.

Concurrent with these efforts by the Federal Government to control smoke from new engines, various states and localities instituted inspection programs designed to limit smoke output from in-use vehicles. Many of these inspection programs, such as that of the State of California(9), rely on the use of Ringelman smoke rating charts by trained observers. The State of New Jersey has recently enacted legislation requiring periodic smoke inspections of all diesel-powered trucks and buses operated on public roads(10). The New Jersey law established a test procedure that recognizes the inherent limitations of the visual (Ringelman) method of rating diesel smoke and requires the use of a light-extinction smokemeter for the inspection.

To meet the instrumentation requirements of present and future inspection programs, various companies have developed smokemeters designed for this particular application. Such instruments are usually portable, have their own internal power supply, and can be operated by one person. Hence, they are not laboratory research instruments, as is the PHS instrument, but rather are designed for use in situations where use of the PHS smokemeter would be impractical.

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*Superscript numbers in parentheses refer to the List of References at the end of this report

Smoke test procedures have also received considerable attention as a result of current or anticipated inspection programs. Such test procedures must be performed in the field, either on the road or on a chassis dynamometer, and should result in smoke measurements typical of vehicle operation. Hence, these test procedures are not necessarily similar to the Federal smoke compliance test, but, like the inspection-type commercial smoke-meters, are designed for a particular application.

The preceding paragraphs present a brief outline of the evolution and present state of diesel smoke control programs, particularly at the Federal and state levels. The project that is the subject of this report was designed to obtain information on some of the pertinent test procedures and commercial smokemeters now in existence and compare them to the accepted standards, the Federal smoke compliance test and the PHS smokemeter. A more general project objective was to gather information on selected aspects of smoke opacity measurement, such as end-of-line and in-the-line sampling methods. Several of these selected topics were investigated at the request of the Project Officer, after consultation with members of the Emissions Research Laboratory staff.

II. EVALUATION OF SMOKE TEST PROCEDURES

The Emissions Research Laboratory has successfully developed a chassis-dynamometer version of the Federal smoke test that correlates well with the engine dynamometer test procedure (Appendix A). This simulated Federal test has, in fact, been the basis for a two-year surveillance study for EPA of smoke from a variety of diesel-powered vehicles (Contract EHS 70-109, "Surveillance Study of Smoke From Heavy-Duty Diesel-Powered Vehicles -- Southwestern U.S.A.")(11).

In 1971, the State of New Jersey began enforcing limits on visible smoke from diesel-powered vehicles operated on its public roads. Several inspection smoke test procedures were investigated by New Jersey officials, including a free acceleration test, a lugdown procedure for trucks, and an acceleration smoke test for buses. The latter two procedures, contained in Appendix B, are currently in use in the New Jersey inspection program.

This phase of the project sought to establish the degree of correlation between these three test procedures and the simulated Federal test. Also, an experimental smoke test was developed by the Emissions Research Laboratory and included in this evaluation study.

A. Description of Test Instrumentation and Facilities

The U. S. Public Health Service full-flow, light-extinction smokemeter (Figure 1) was used to measure exhaust smoke opacity during all test procedures. Smokemeter output and engine speed were recorded on a Texas Instruments or Hewlett Packard dual-pen recorder with 10-mv range and 0.4 sec full-scale response. Recorder chart speed was 12 in per minute, which permitted accurate analysis of the opacity traces. The vehicles used in this evaluation were operated on a Clayton chassis dynamometer with tandem-axle power absorption capability. This unit can absorb 200 hp per axle, while simulating up to 41,000 pounds of vehicle weight by means of inertia wheels attached to the dynamometer rolls. Figure 2 shows a bus under test on this dynamometer.

B. Description of Smoke Test Procedures

The smoke test procedures used in this study included the chassis dynamometer simulation of the Federal smoke compliance test, the New Jersey lug-down test for trucks, the New Jersey acceleration test for buses, an experimental smoke test developed by the Emissions Research Laboratory, and a free acceleration test formerly proposed as the New Jersey test for trucks. These various procedures will now be described in detail.

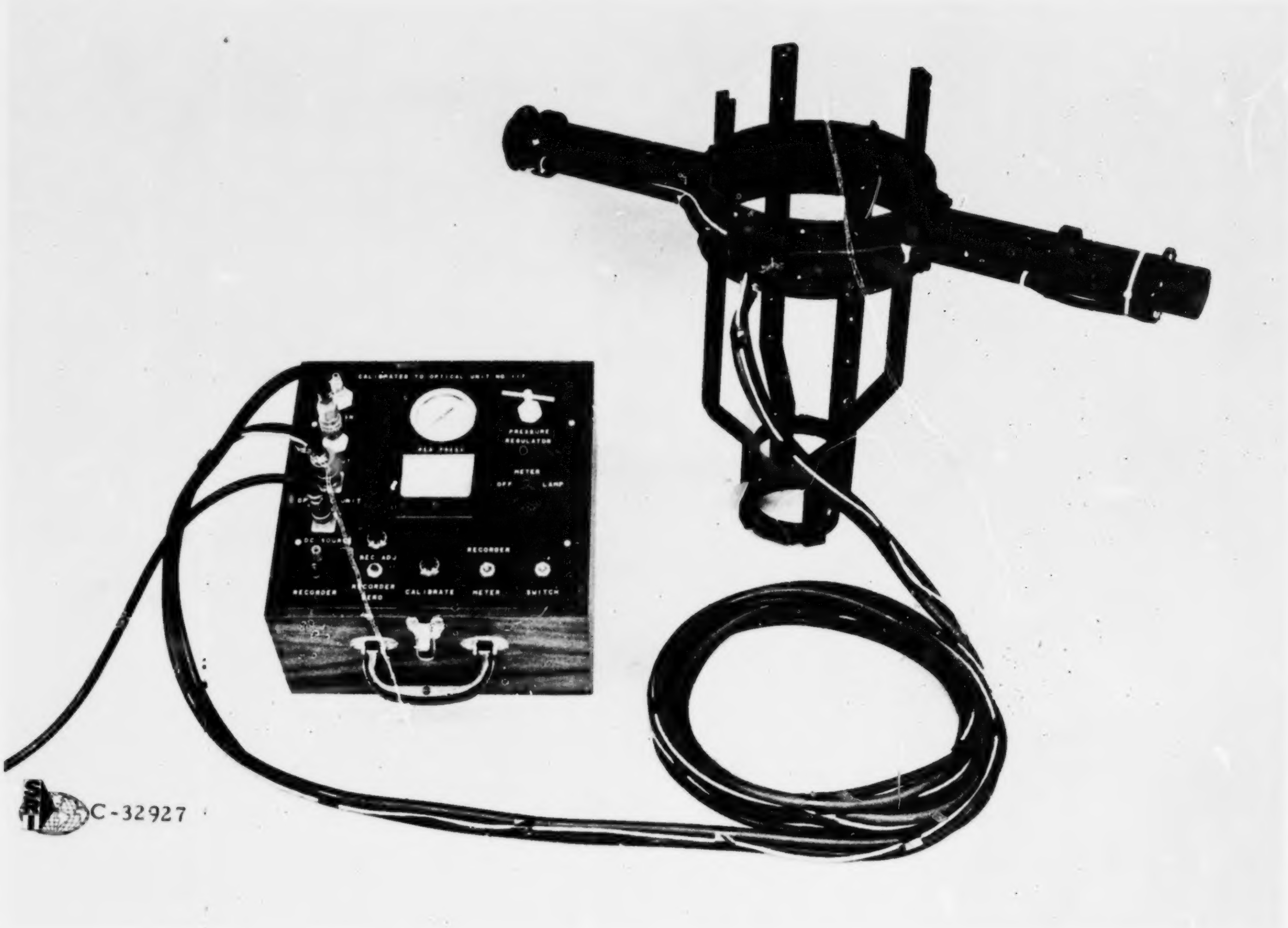
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FIGURE 1. PHS FULL-FLOW, LIGHT-EXTINCTION SMOKEMETER

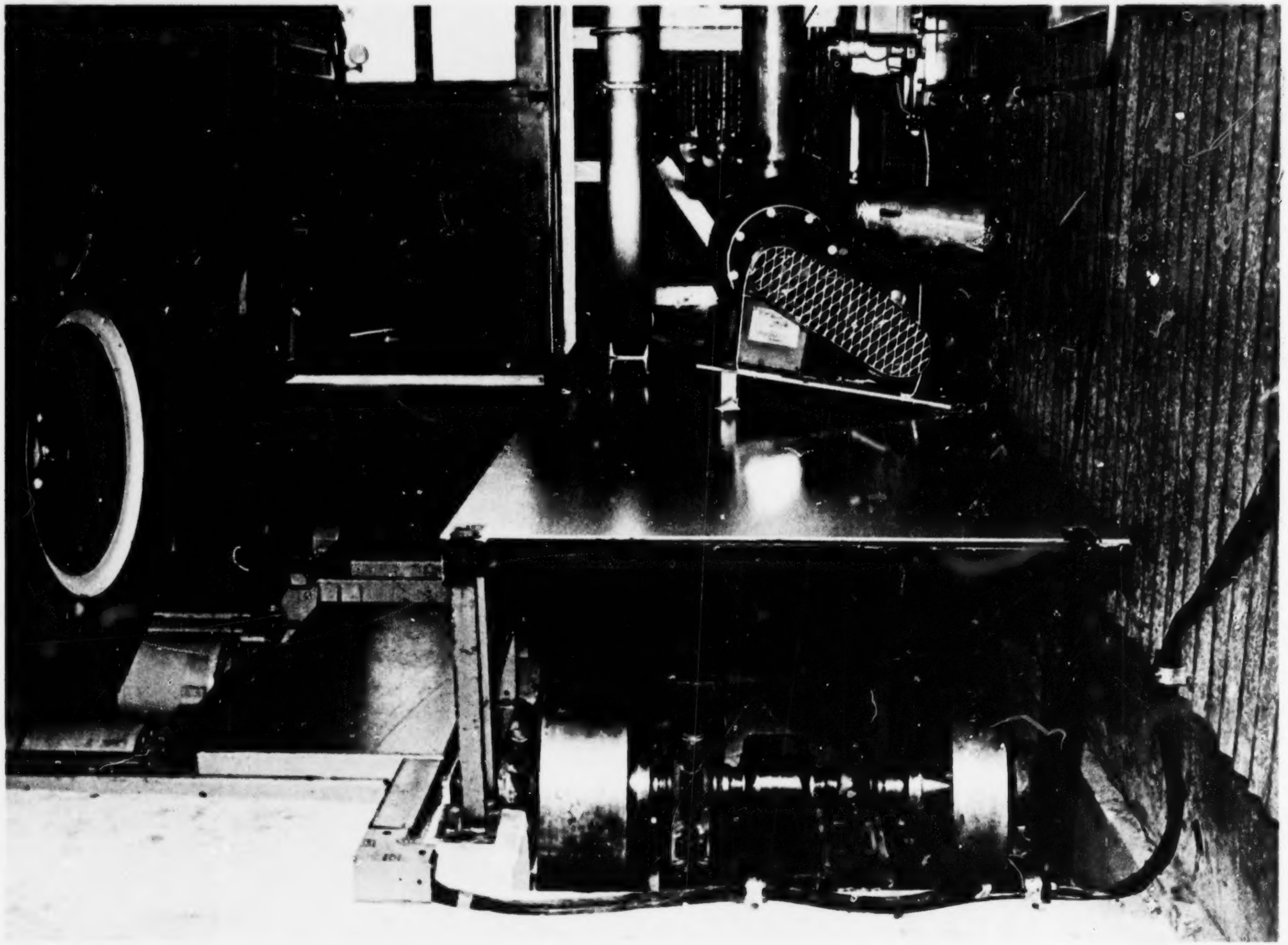

FIGURE 2. CITY BUS UNDER TEST ON SwRI DYNAMOMETER (INERTIA SIMULATION WHEELS IN RIGHT FOREGROUND)

The Federal smoke compliance test, as performed on engine or chassis dynamometer, consists of an initial engine acceleration from 150-250 rpm above idle speed to 85-90% of rated engine speed in 5.0±1.5 seconds, a second acceleration from peak torque speed (or 60% of rated speed, whichever is higher) to 95-100% of rated speed in 10.0±2.0 seconds, and (following this second acceleration) a full-power lugdown from 95-100% of rated speed to the particular intermediate engine speed (peak torque speed or 60% of rated speed) in 35.0±5 seconds. The accelerations are made against simulated vehicle inertia furnished by large flywheels connected to the dynamometer rolls or shaft, and/or against a preset load in the power absorption unit. A schematic drawing of engine speed vs time is illustrated in Figure 3. Three of these sequences constitute one smoke test.

The average smoke opacity from the 15 highest - valued one-half second intervals of the two accelerations determine the "a" factor, and the average opacity from the five highest - valued one-half second intervals determines the "b" factor. The maximum values currently allowed for "a" and "b" factors of certification engines are 40- and 20- percent opacity, respectively.

The New Jersey lugdown smoke test for trucks can be conducted on a chassis dynamometer or on the road. In the latter procedure, the full-power lugdown of the engine is accomplished by applying the vehicle brakes. The chassis dynamometer test, which was used in this evaluation, consists first of operating the engine at maximum governed engine speed, under no load, in a transmission gear that gives a vehicle speed of 45-60 mph. (Note that the engine speed involved is the maximum allowed by the governor, and is usually 100-250 rpm over the rated engine speed designated in the manufacturer's sales and service literature.) Power absorption (load) is applied until the engine speed is reduced to 80% of maximum governed rpm. This reduced engine speed is held constant for 5-10 seconds, and the peak smoke opacity measured during this time is the opacity value for the test. The maximum peak opacity allowed under current New Jersey law is 20 percent. Figure 4 is a schematic drawing of engine speed vs time for this procedure.

The New Jersey acceleration smoke test for buses is conducted on the road and involves a full-throttle acceleration from rest to a vehicle speed of 20 mph. The peak smoke opacity generated during this acceleration period (approximately 8-12 seconds) is the test opacity. A peak of 40 percent opacity is the maximum allowed under current New Jersey law. A schematic drawing of vehicle speed vs time for this procedure is shown in Figure 5.

The experimental smoke test developed by the Emissions Research Laboratory is a chassis dynamometer procedure. The

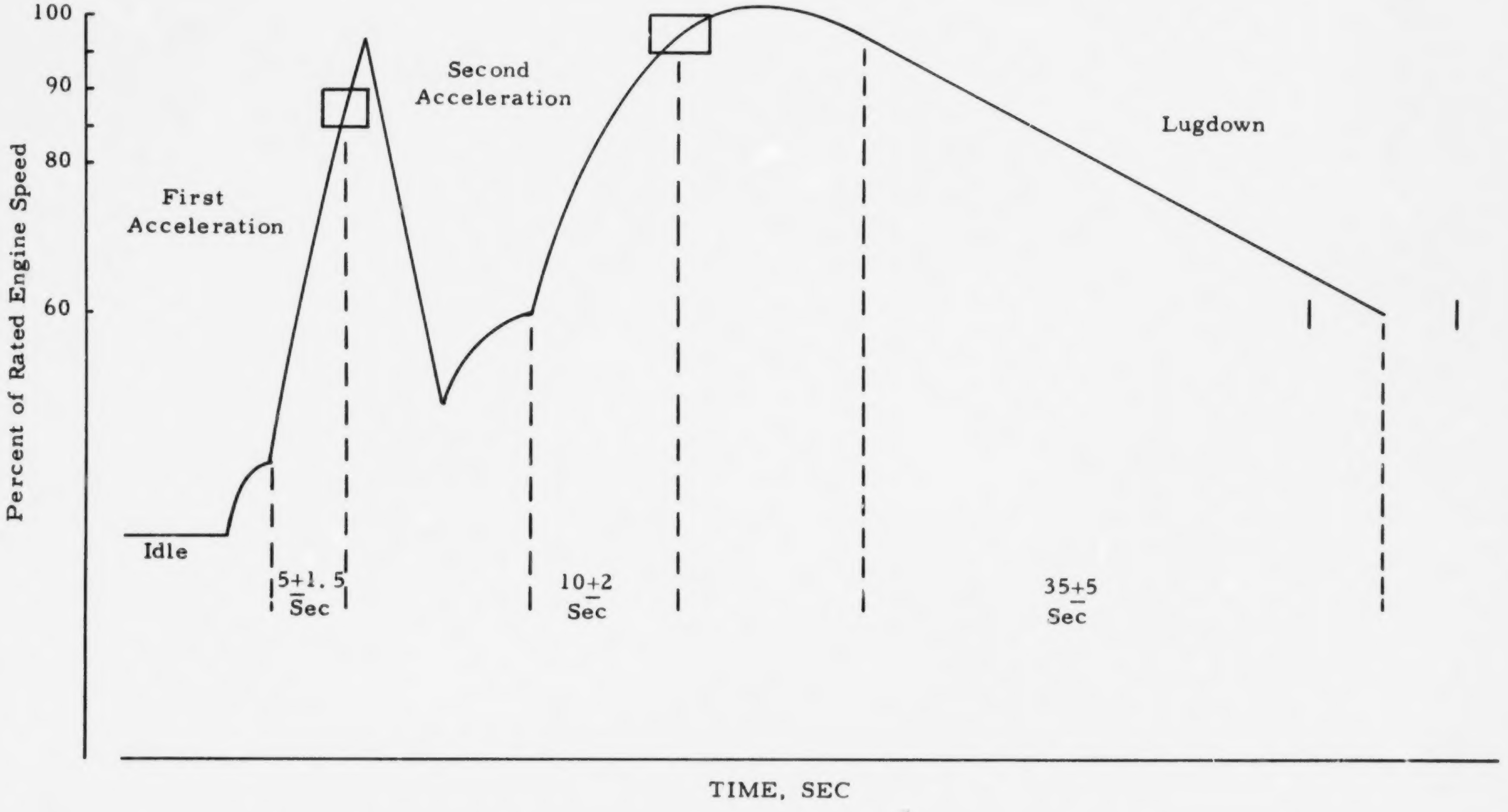

FIGURE 3. SCHEMATIC OF FEDERAL SMOKE COMPLIANCE TEST - ENGINE SPEED VS TIME

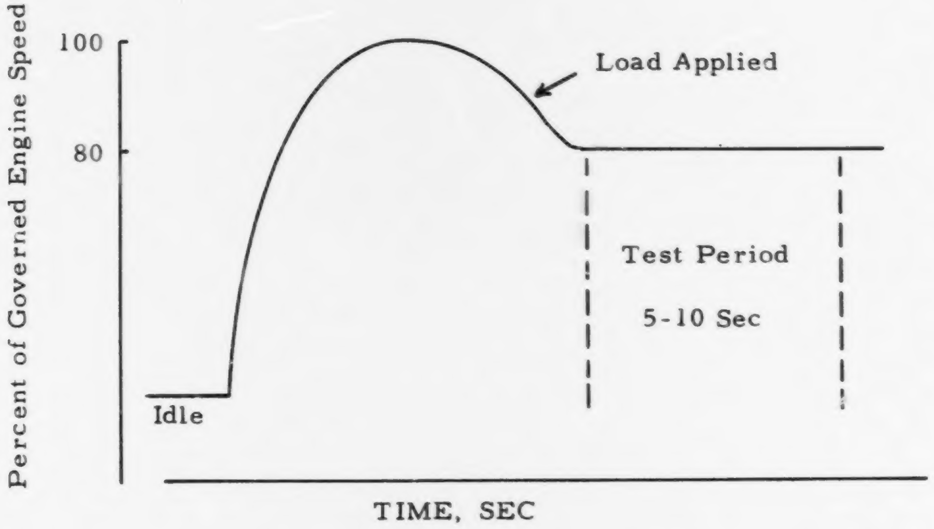

FIGURE 4. SCHEMATIC OF NEW JERSEY LUGDOWN SMOKE TEST - ENGINE SPEED VS TIME

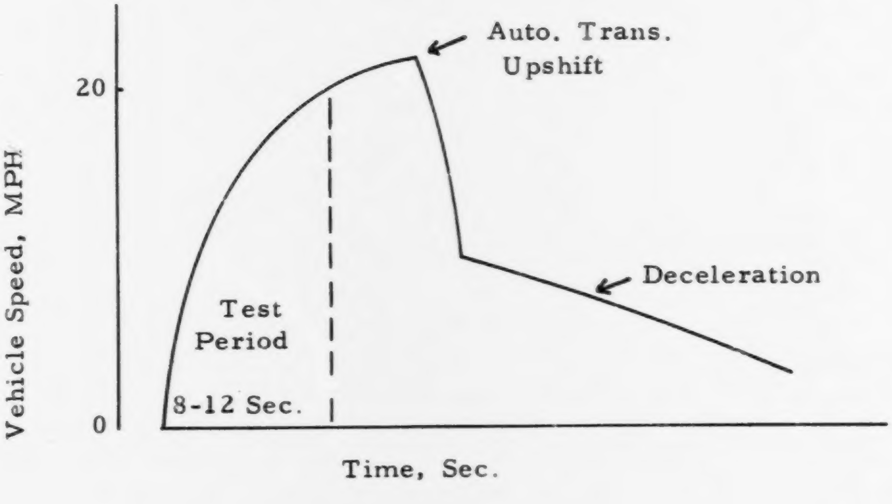

FIGURE 5. SCHEMATIC OF NEW JERSEY ACCELERATION SMOKE TEST - VEHICLE SPEED VS TIME

engine in the test vehicle is first operated at rated speed and maximum power output, and a transmission gear is selected that produces a rear wheel speed of 45-65 mph. The engine is then brought back to low idle speed and the rear wheels brought to rest. The dynamometer load used to obtain the maximum power condition is left in the water brake power absorption unit. The smoke test itself consists of engaging the vehicle's clutch in a smooth and steady manner, then accelerating with full throttle. (Buses with two-speed automatic transmissions are accelerated at full throttle and the transmission upshift allowed to occur as in normal operation.) Engine speed increases quite rapidly at first, due to the absence of any inertia simulation flywheels on the dynamometer rolls. However, as engine speed (and, hence, rear wheel speed) increases, the load stored in the water brake unit becomes effective, and engine speed increases at a slower rate. Approximately five to ten seconds after the start of the accelerations, engine rpm reaches rated speed, the maximum attainable with the preset load in the dynamometer. This maximum power condition at rated engine speed is maintained for approximately 10 seconds. Schematic drawings of engine speed vs time for this procedure for trucks and buses are shown in Figures 6 and 7, respectively.

The smoke opacity trace produced during the acceleration and the maximum power condition is analyzed to obtain both peak and average opacity. This latter quantity is obtained by averaging the smoke opacity in the five highest - valued one-half second intervals.

The free acceleration test is performed with the vehicle at rest and the transmission in neutral. The engine undergoes a full-throttle acceleration from 1000-1200 rpm to maximum governed engine speed. As soon as this maximum speed is reached, the throttle is partially closed and engine speed allowed to drop back to the 1000-1200 rpm range. The engine is again accelerated to maximum speed. This test cycle is repeated several times, until three or four repeatable peak opacity readings are obtained. Only peak opacity is of interest, since the acceleration time is very short (usually one second or less) and time-averaged opacity is therefore less informative than when the acceleration is of longer duration.

C. Description of Test Vehicles and Engines

The makes and models of engines used in this study were selected to fulfill several criteria imposed by the evaluation procedure. For the evaluation of smoke tests of diesel-powered trucks, engines were selected which provided a wide range of smoke opacities and exhaust flow rates. Additional consideration was given to the operating characteristics of the engines, such as whether their highest smoke opacity occurred during acceleration or lugdown, and if the acceleration smoke peaks were of long or short duration.

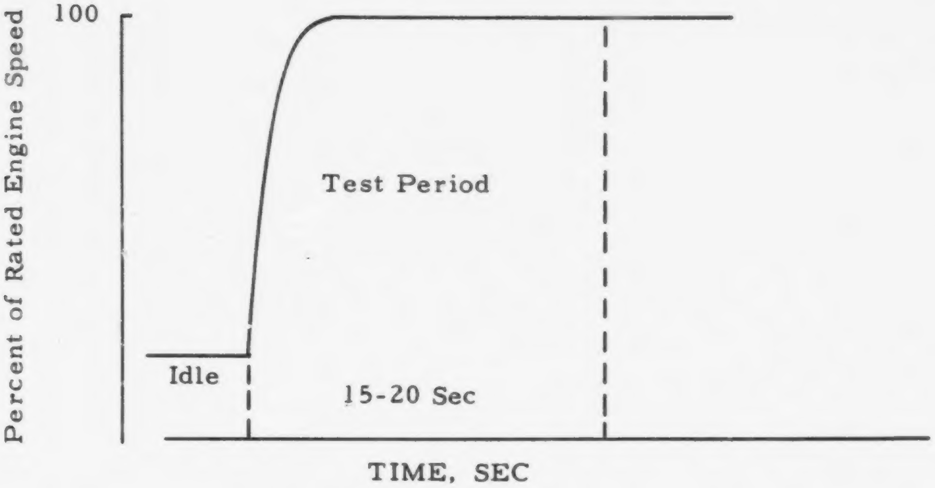

FIGURE 6. SCHEMATIC OF EXPERIMENTAL SWRI SMOKE TEST FOR TRUCKS - ENGINE SPEED VS TIME

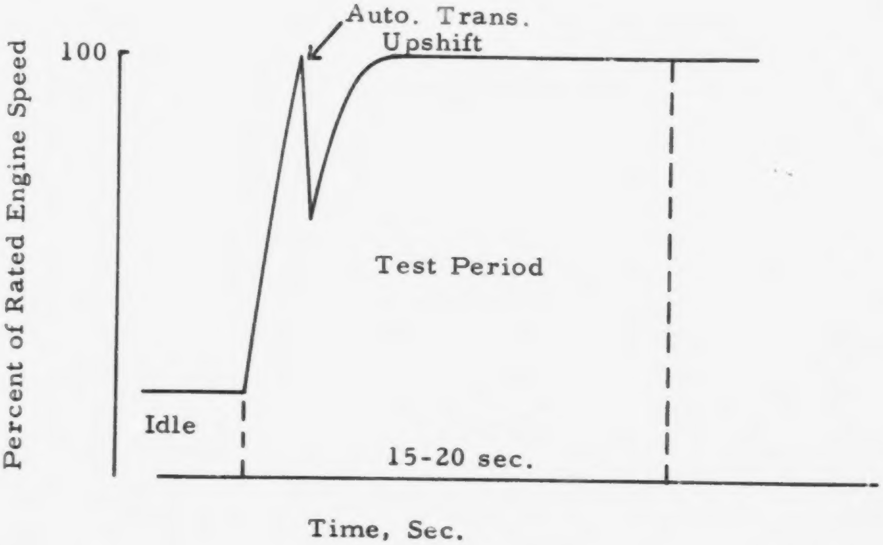

FIGURE 7. SCHEMATIC OF EXPERIMENTAL SwRI SMOKE TEST FOR BUSES - ENGINE SPEED VS TIME

The Cummins NHC-250 and NTC-335 engines used in these tests were installed in intercity truck-tractors equipped with tandem-drive rear axles and single four-in diameter exhaust stacks. The two naturally aspirated NHC-250 engines originally had approximately the same smoke opacity; however, for test purposes one engine had its smoke level increased substantially by the insertion of a restrictor plate in the intake manifold. The turbocharged NTC-335 engine had high peak opacity during acceleration from idle and very low smoke during high-power constant speed (or slow lugdown) conditions. The Caterpillar 1150 engine was installed in a single-axle truck-tractor used in intracity service. This naturally aspirated engine had very high, very brief smoke peaks during acceleration from idle, and lugdown smoke similar to an NHC-250 engine. The Caterpillar 1150 thus had smoke output typical of both naturally aspirated and turbocharged engines.

For the evaluation of tests for diesel-powered buses, the only engine available was the Detroit Diesel 6V-71 two-cycle engine common to most municipal buses. Since these engines all have approximately the same fuel and air consumption rates, the only variable of significance was the smoke opacity. Hence, it was decided to use one bus for all tests and to vary the smoke opacity by means of a series of plate orifices installed in the engine's air intake system. This approach, which was approved by the Project Officer, proved to be very effective. Any desired smoke level could be obtained with the proper plate orifice, and the smoke opacity was highly repeatable from one test to another. The nominal smoke levels used in this evaluation were approximately 6.0, 13.0, 22.0, and 36.5- percent opacity.

D. PHS Smokemeter Data for Four Smoke Test Procedures

The data contained in this section are results from all smoke tests performed with the five test vehicles (four truck-tractors and one bus) and are the average of at least six repeatable tests with each test procedure, with each vehicle. In the case of the city bus, the various tests were performed at least six times at each of the four smoke levels. The data for the truck smoke tests are presented separately from those for the bus smoke tests.

1. Truck Smoke Tests

Table 1 contains the data for the smoke tests involving the four truck-tractors. The time-averaged data for the accelerations and lugdowns (or other full-power conditions) are given as "a" and "b" factors, respectively. These terms are generally used to denote the time-averaged data for the Federal smoke test, and are used here in an

TABLE 1. PHS SMOKEMETER DATA FOR FOUR TEST PROCEDURES FOR DIESEL-POWERED TRUCKS

	Federal (Chassis Dyna.) PHS Smoke Opacity, %				New Jersey Truck Lugdown PHS Smoke Opacity, %			
Engine	"a" Factor*	Accel. Peak	"b" Factor*	Lug Peak	"a" Factor*	Accel. Peak	"b" Factor*	Lug Peak
Cummins NHC-250 (No. 1)	13.5	24.2	12.2	16.1	9.6	20.8	8.8	10.8
Cummins NHC-250 (No. 2)	35.1	38.8	38.0	40.4	18.0	29.1	31.4	32.4
Cummins NTC-335	10.2	38.8	2.6	3.0	42.2	64.0	2.2	2.8
Caterpillar 1150	27.2	97.1	24.9	27.4	22.0	79.4	12.6	17.9

	SwRI Accel.-Max. Power PHS Smoke Opacity, %				New Jersey Free Accel. PHS Smoke Opacity, %
Engine	"a" Factor*	Accel. Peak	"b" Factor*	Max. Power Peak	Accel. Peak
Cummins NHC-250 (No. 1)	14.2	18.4	14.5	16.3	15.9
Cummins NHC-250 (No. 2)	20.6	29.8	27.0	27.9	29.6
Cummins NTC-335	37.6	50.6	2.4	3.0	59.6
Caterpillar 1150	26.8	89.3	15.4	18.2	23.2

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* Time-Averaged Data

analogous manner for the other test procedures. The "peak" data are the instantaneous peak opacity values obtained during the accelerations and lugdown (or other full-power conditions) of the various test procedures.

There are two general comparisons made with the data in Table 1. First, the time-averaged "a" and "b" factors for a particular test procedure are compared to the corresponding peak values for the same procedure. However, the principle comparison is between the data for the simulated Federal smoke test and those for the other three test procedures. These comparisons, especially the latter, are quite involved; therefore, the data is illustrated (Figures 8, 9, 10 and 11) in an attempt to facilitate the various comparisons. Some remarks concerning the general trends demonstrated by the data will be made, but the reader will find frequent references to the aforementioned figures, and Table 1, helpful.

a. Comparison of Average and Peak Opacity Data

As one would expect, the peak opacities were in every instance higher than the time-averaged opacities. The magnitude of the differences between the peak and time-averaged data was greatest for the acceleration smoke opacities of the Cummins NTC-335 and Caterpillar 1150 engines, since they have high peak smoke during acceleration from idle. In the case of the two Cummins NHC-250 engines, the greatest difference between peak and average acceleration opacities occurred for Engine No. 1, the "low smoke" engine. This was due to the fact that the "high smoke" engine (No. 2) had acceleration smoke traces with a broad, almost square-wave form, while the low smoke engine had a definite peak to its smoke trace. Thus, the peak acceleration opacity for the high smoke engine was closer to its time-averaged "a" factor than was the case for the low smoke engine.

The greatest difference between the time-averaged "b" factors and their corresponding peak values occurred for the Caterpillar 1150 engine, and was least for the Cummins NTC-335 engine. The Caterpillar engine has a large variance on either side of its average lugdown opacity value. Such a variance appears as "hash" on the smoke opacity trace. The turbocharged NTC-335 engine produces very smooth opacity traces, with little "hash". This is because the turbocharger damps out most of the pulsations in the exhaust flow. The difference between average and peak lugdown opacity for the NHC-250 engines falls between the two extremes mentioned above. However, the high smoke engine showed slightly better agreement than its low smoke counterpart.

These general observations hold for the three test procedures that have both average and peak opacity data. The free acceleration test data involves only peak opacity values.

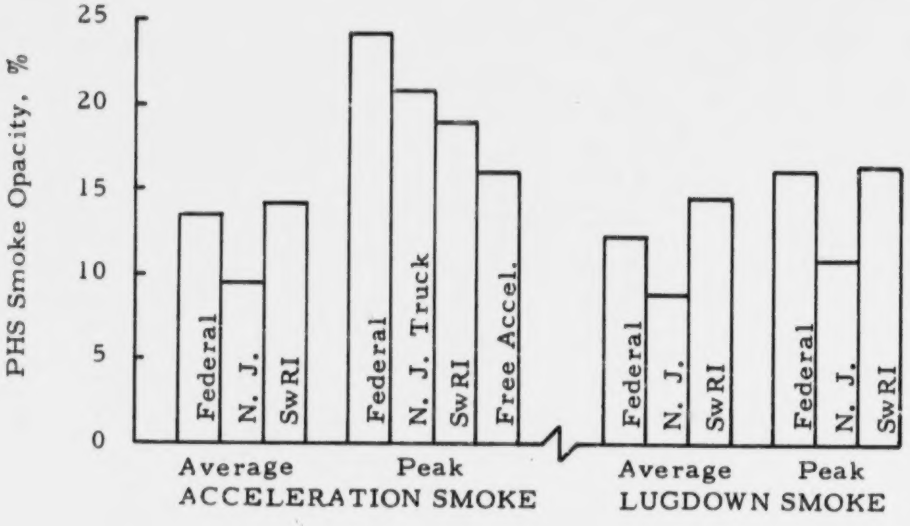

FIGURE 8. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES - CUMMINS NHC - 250 ENGINE (NO. 1)

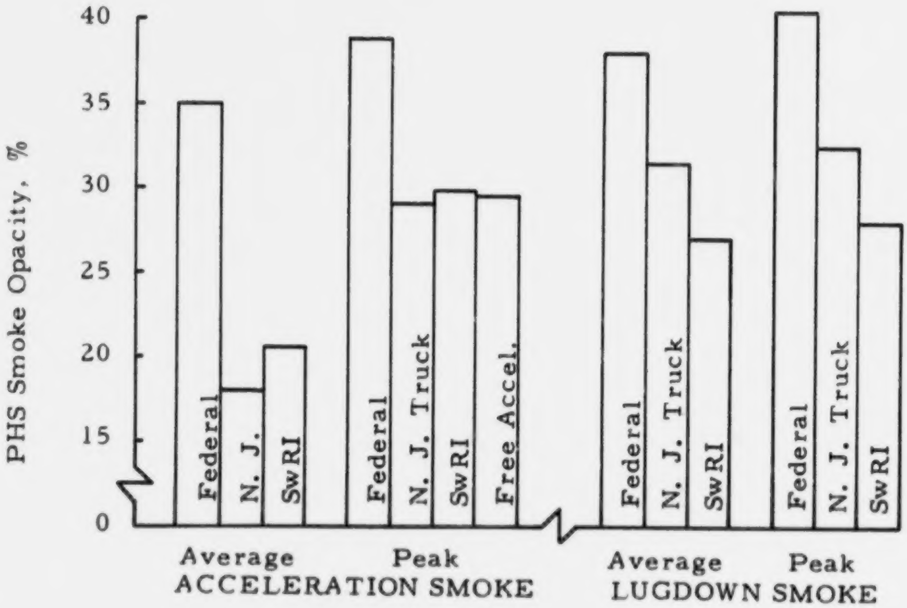

FIGURE 9. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES - CUMMINS NHC - 250 ENGINE (NO. 2)

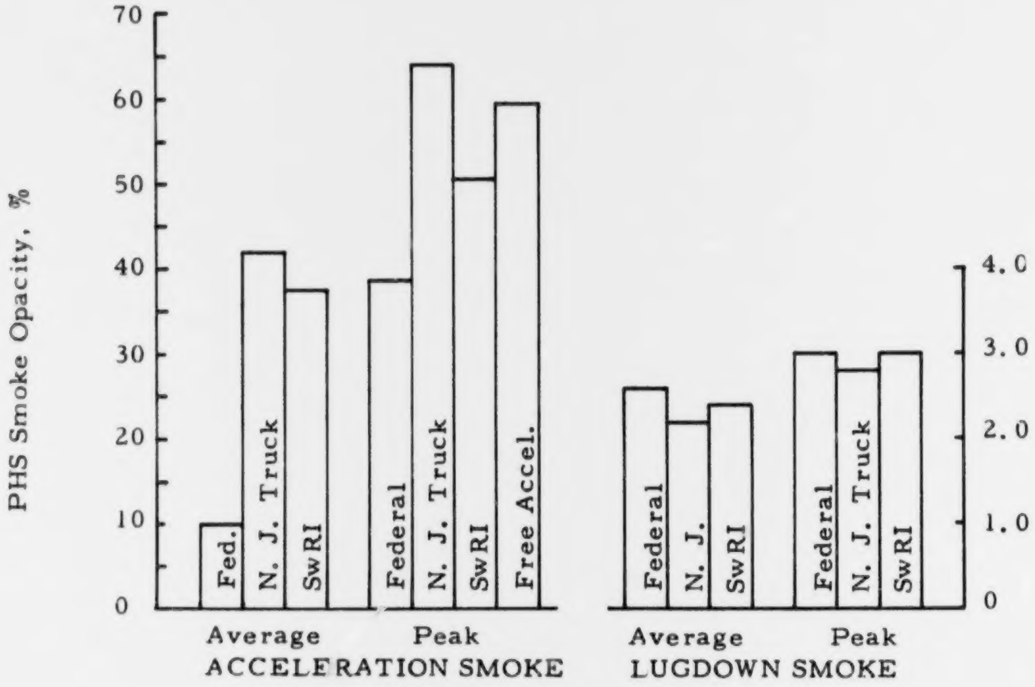

FIGURE 10. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES - CUMMINS NTC-335 ENGINE

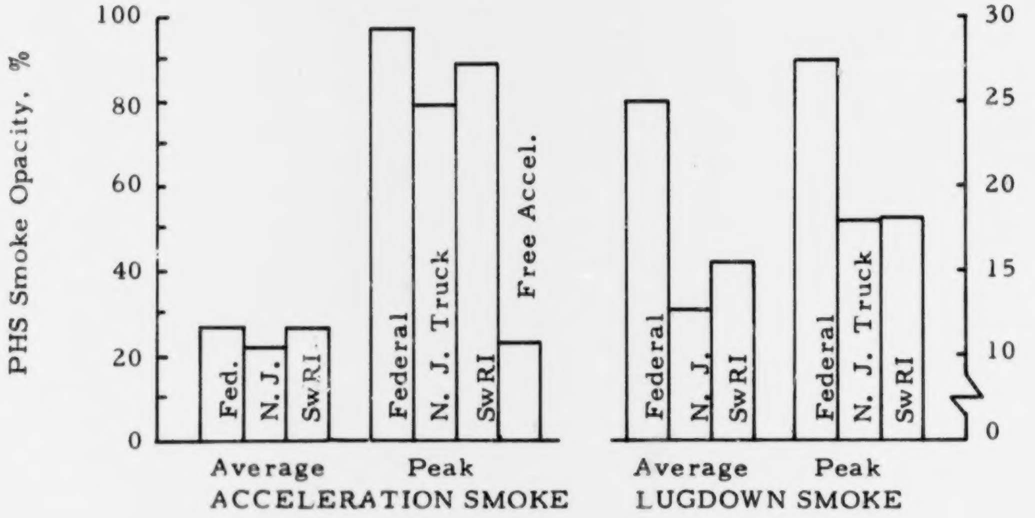

FIGURE 11. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES - CATERPILLAR 1150 ENGINE

b. Comparison of Federal Smoke Test with Other Test Procedures

The "a" factors for the New Jersey lugdown test are substantially lower than those for the simulated Federal Test, except in the case of the turbocharged NTC-335 engine, where the reverse is true. The same trends were found in the peak acceleration opacities for these two procedures. The acceleration in the New Jersey test is very fast, being accomplished without inertia simulation or dynamometer load. This rapid acceleration caused the turbocharged engine to develop significantly higher peak opacity than the slower acceleration against inertia of the Federal smoke test. Hence the higher "a" factor in the New Jersey test.

Similarly, the lugdown smoke opacities, both time-averaged and peak, for the New Jersey test are, in general, significantly lower than those of the Federal test. The turbocharged engine produced very similar opacity readings with each procedure, while the Caterpillar 1150 engine showed the worst correlation. The reason for this discrepancy is that the turbocharged engine produced low smoke at almost any full-power condition, regardless of engine speed. On the other hand, the naturally aspirated 1150 engine produced its highest smoke opacity below 2000 engine rpm. The minimum speed this engine encounters in the Federal and New Jersey test procedures is 1800 and 2400 rpm, respectively. Hence, lugdown smoke was much higher in the Federal test. The NHC-250 engines generate their highest lugdown smoke at approximately 1800-2000 rpm, and this speed range is covered in the Federal test. However, the New Jersey procedure is run at 1840 engine rpm, where smoke opacity is somewhat less.

The "a" factors for the SwRI test cycle show varying degrees of correlation with the Federal smoke test "a" factors. The best agreement exists for the low smoke (No. 1) Cummins NHC-250 engine and the Caterpillar 1150 engine. The SwRI "a" factor generated by the high smoke (No. 2) NHC-250 is much lower, and that of the turbocharged NTC-335 engine much higher, than the corresponding "a" factors for the simulated Federal test. The peak acceleration opacities for the SwRI test were moderately (6- to 9- percent opacity) lower than the corresponding peak data for the Federal test cycle, except for the turbocharged NTC-335 engine, where the reverse situation occurs. The typical acceleration in the SwRI test requires a time span somewhere between those required for the Federal and New Jersey procedures, and the acceleration smoke opacity, both peak and time-averaged, for the turbocharged engine appears to increase as the duration of the acceleration decreases.

The SwRI "b" factors and peak opacities for the low smoke (No. 1) NHC-250 and NTC-335 engines are close to those for the Federal test. However, the high smoke (No. 2) NHC-250 and Caterpillar 1150 engines show very poor correlation between the two test procedures. All three of the Cummins engines are operated at 2100 rpm in the SwRI test, while the Caterpillar engine is tested at 3000 rpm In view of what was said previously concerning the speeds at which these engines produce their maximum steady-state smoke opacity, it is not surprising that the Caterpillar engine shows such poor correlation between these two procedures. Conversely, one would expect that the NHC-250 engines would show good correlation, since they are operated near the speed where their maximum smoke opacity occurs. It is not known why the high smoke NHC-250 did not have better correlation between the two types of tests.

The peak opacities for the free acceleration tests do not correlate well with the acceleration peaks of the Federal smoke test. However, the free acceleration peaks are surprisingly close (2.5- to 5.5- percent opacity) to the "a" factors for the naturally aspirated engines in the Federal procedure. The turbocharged NTC-335 engine produces a free acceleration peak approximately six times the value of the time-averaged Federal "a" factor.

In summary, the SwRI smoke test shows good "a" factor correlation with the Federal test for two naturally aspirated engines used in the evaluation. The time-averaged acceleration opacity from the New Jersey lugdown test does not adequately reproduce the Federal "a" factors for any of the engines. The free acceleration has some correlation with the Federal "a" factors for the naturally aspirated engines, but would appear to have serious problems with smoke from turbocharged engines. Both the New Jersey lugdown and SwRI tests are capable of reproducing the Federal "b" factor for the turbocharged engine, but not for the naturally aspirated engines. Thus, no one procedure correlates with the simulated Federal smoke test in every instance.

2. Bus Smoke Tests

The data from the smoke tests performed by the municipal bus are presented in Table 2. Again, the "a" and "b" factors are time-averaged opacities for accelerations and lugdowns, respectively, while the "peak" data are instantaneous opacity values. As in the case of the truck test data, there are two comparisons of interest. First, time-averaged opacities ("a" and "b" factors) for a test procedure are compared to the corresponding peak opacities for the same procedure. The second and more important comparison is between the Federal smoke test data and the data for the other procedures. These comparisons are represented graphically in Figures 12, 13, 14 and 15.

TABLE 2. PHS SMOKEMETER DATA FOR FOUR TEST PROCEDURES FOR DIESEL-POWERED BUSES

Engine	Federal (Chassis Dyna.) PHS Smoke Opacity, %				New Jersey Bus Accel. PHS Smoke Opacity, %	
	"a" Factor*	Accel. Peak	"b" Factor*	Lug Peak	"a" Factor*	Accel. Peak
Detroit Diesel 6V-71E	5.2	7.2	5.6	6.0	3.5	4.4
Detroit Diesel 6V-71E	13.2	15.6	12.8	14.2	8.0	10.4
Detroit Diesel 6V-71E	21.9	25.0	21.7	22.8	14.2	18.2
Detroit Diesel 6V-71E	37.6	43.4	36.4	38.7	20.0	25.1

Engine	SwRI Accel. - Max. Power PHS Smoke Opacity, %				New Jersey Free Accel. PHS Smoke Opacity, %
	"a" Factor*	Accel. Peak	"b" Factor*	Max. Power Peak	Accel. Peak
Detroit Diesel 6V-71E	4.1	4.4	4.4	4.9	4.6
Detroit Diesel 6V-71E	10.3	14.0	13.6	14.6	17.0
Detroit Diesel 6V-71E	19.5	24.2	24.2	25.6	34.5
Detroit Diesel 6V-71E	28.6	34.5	38.9	41.2	47.8

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*Time Averaged Data

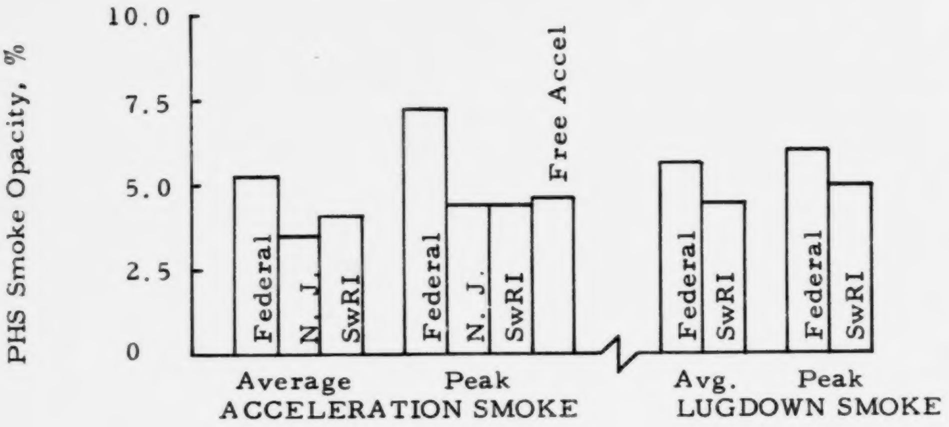


FIGURE 12. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES -- 6V-71 ENGINE AT FIRST SMOKE LEVEL

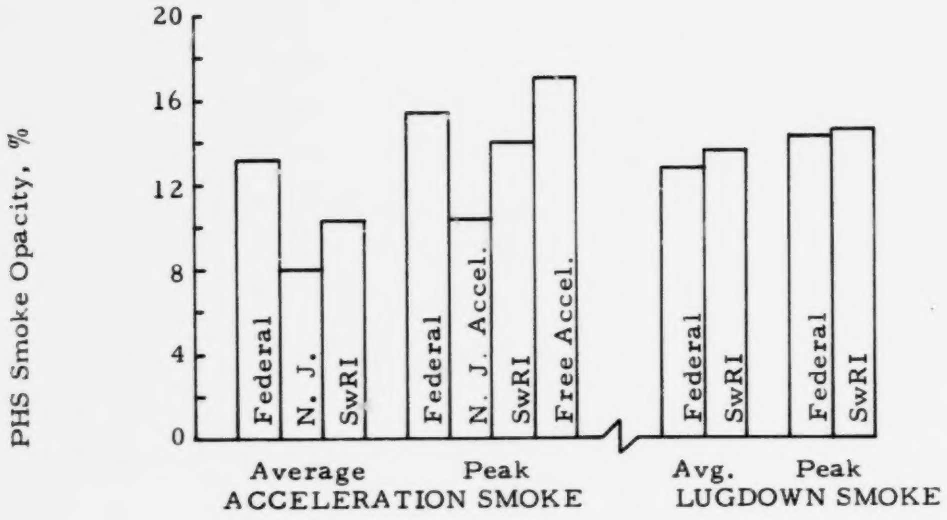


FIGURE 13. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES -- 6V-71 ENGINE AT SECOND SMOKE LEVEL

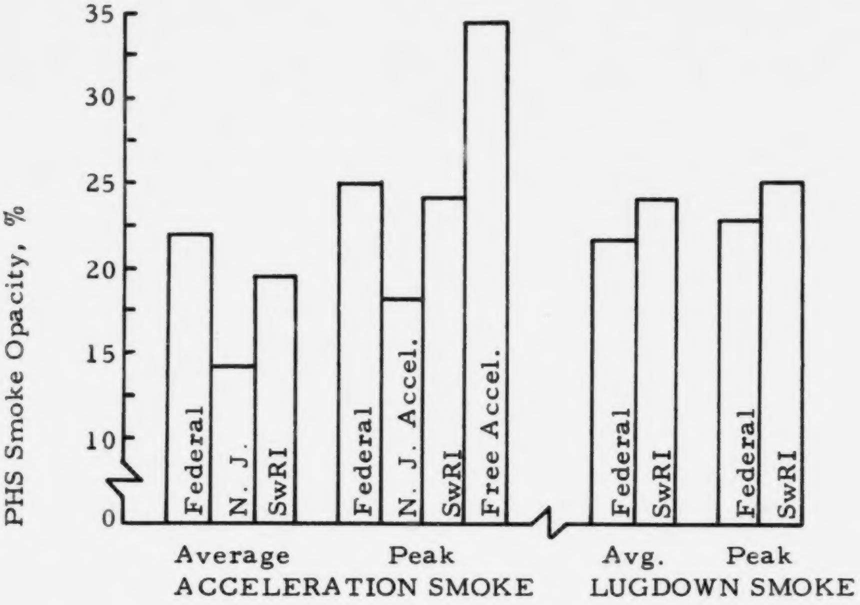


FIGURE 14. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES -- 6V-71 ENGINE AT THIRD SMOKE LEVEL

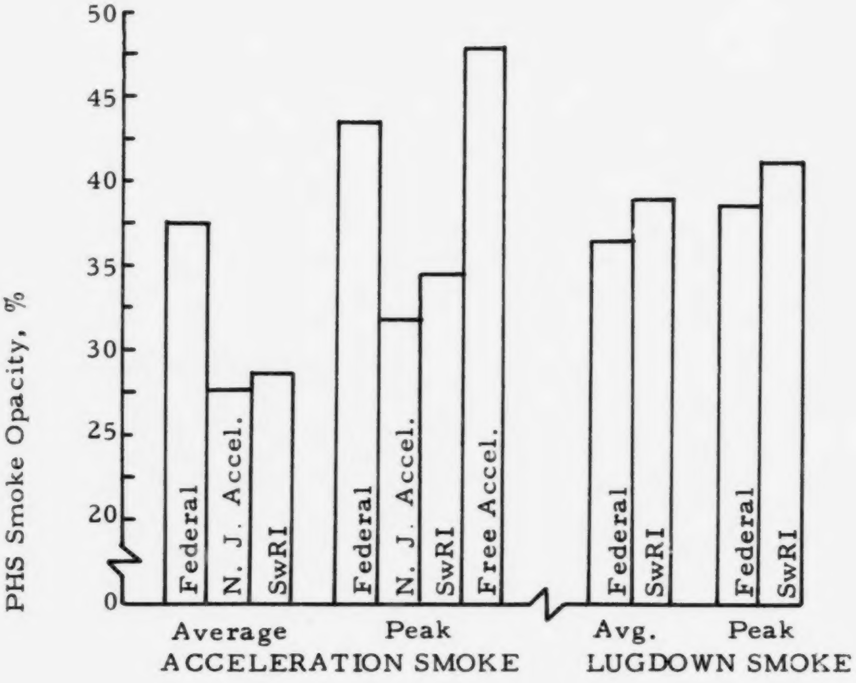


FIGURE 15. PHS OPACITY DATA FOR FOUR SMOKE TEST PROCEDURES -- 6V-71 ENGINE AT FOURTH SMOKE LEVEL

a. Comparison of Average and Peak Opacity Data

As in the case of the truck smoke test data, the peak opacities of both accelerations and lugdown were higher than the corresponding average opacities, and the difference between peak and average opacity tended to increase as the smoke level increases. This trend is most evident for the acceleration smoke opacity data and is consistent for the Federal, New Jersey, and SwRI tests. There is very little "hash" in the smoke opacity trace of a two-cycle engine. Hence, the differences between the time-averaged and peak opacities are not so dependent on the variance in the opacity trace as in the case of the smoke tests with the four-cycle truck engines.

The simulated Federal test produced acceleration smoke peaks some 2.0- to 6.0- percent opacity higher than the average value of the acceleration smoke. The peak opacities during lugdown were generally within 1.0- or 2.0- percent opacity of the time-averaged opacities for this part of the test procedure. The peak opacity values for the New Jersey acceleration test were 1.0- to 5.0- percent opacity greater than the time-averaged values. No lugdown data are produced by the New Jersey test. The experimental SwRI smoke test had acceleration smoke peaks approximately 0.3- to 6.0- percent opacity higher than the corresponding "a" factors, while the steady-state maximum power smoke had peaks some 0.5- to 2.5- percent opacity higher than the time-averaged opacities.

b. Comparison of Federal Smoke Test With Other Procedures

The New Jersey smoke test for buses produced substantially lower opacities, both peak and average, than the simulated Federal test. Also, this difference increased as the nominal smoke level increased. In actual practice the New Jersey inspection program is concerned only with the peak acceleration opacity produced by the test. Hence, it is interesting to compare the peak opacity with the time-averaged Federal "a" factors. The peak New Jersey data are consistently lower than the corresponding Federal "a" factors, in spite of the fact that the Federal "a" factors are partially determined by the usually lower opacity values from the second acceleration in that procedure. Other factors that contribute to the differences in opacity between these two procedures are the longer duration of the New Jersey acceleration (almost twice as long as the initial acceleration of the Federal test) and the lower engine speed attained during the New Jersey test (1600 rpm N2 1800 rpm for the first acceleration of the Federal test). Slower acceleration rates in particular appear to be the reason for lower smoke opacity than would otherwise be produced.

The experimental SwRI smoke test produced peak and time-averaged acceleration opacities at the first three smoke levels that were slightly lower than the corresponding opacities from the Federal smoke test. Only at the highest smoke level (a nominal 36.5- percent opacity) was there a large deviation for the two sets of data. The average and peak opacities for the lugging (or maximum power) part of the SwRI cycle were close to (and slightly higher than) the lugdown opacities of the Federal test procedure, even at the highest smoke level. This agreement between the data for the two procedures is the result of the fast acceleration time (approximately 2.0 seconds) and lugdown at rated speed in the SwRI test. These conditions are closer to those in the Federal test than are the conditions of the New Jersey procedure; hence, correlation with the Federal test is better.

The free acceleration test produced peak opacities that were, in general, substantially higher than the "a" factors of the Federal smoke test. The greatest difference again occurred at the higher smoke levels. The correlation between the free acceleration peak opacities and the acceleration peaks of the Federal test was inconsistent, in some cases being fairly close and in others being very poor.

Overall, the results of the experimental SwRI smoke test procedure showed the best agreement with the Federal test data, particularly for smoke levels below, say, 25- percent opacity. The "a" factors of the New Jersey test correlate very badly with the Federal "a" factors. However, a certain degree of correlation does exist between the peak opacities of the New Jersey test and the Federal "a" factors, but only for opacity levels under about 20 percent. This same conclusion also applies to the free acceleration peak opacities. Therefor, in summary, none of the test procedures correlated with the simulated Federal test in all cases.

III. EVALUATION OF THREE COMMERCIAL SMOKEMETERS

The recent emphasis on state inspection programs for diesel-powered vehicles has caused several companies to develop opacity measurement devices for this application. In particular, the New Jersey Department of Environmental Protection requested that interested companies submit designs for a smokemeter to be used in that state's inspection program. Three companies which offered their smokemeters for consideration by New Jersey officials were Atlantic Research Corporation, Bacharach Instrument Company and Nebetco Engineering. The Atlantic Research instrument was eventually selected by New Jersey for use in the program.

However, the potential market for these inspection-type smokemeters is still quite large, with other state and local enforcement agencies, fleet owners, municipal transit (bus) concerns, and even diesel repair shops all potential buyers of this type of instrument. Hence, there exists a need for a performance evaluation of these smokemeters, particularly in comparison with the PHS instrument. The Atlantic Research, Bacharach, and Nebetco smokemeters were the instruments included in this evaluation, and their performance characteristics were defined in a broad series of tests.

A. Description of Commercial Smokemeters

The Atlantic Research instrument (Figure 16) is a portable, battery-powered unit designed to meet specifications of the State of New Jersey. The instrument consists of a sensor unit containing the light source and optical detector, and a hand-held readout unit containing operating controls, meter, electrical circuitry, and power supply. The two units are connected by a signal cable. The light source is a solid-state device operating at a frequency of 1000 Hz. The optical detector is a solid-state photodiode. Electrical circuitry is also solid-state, and utilizes integrated circuits and printed wiring. The batteries are of the permanent rechargeable type and can be recharged by plugging the readout unit into a 120-volt AC outlet overnight. Operating controls in the hand unit are an on-off switch, "zero" and "full-scale" adjustments, and a button that gives the user a choice of either continuous or peak opacity readings. The smokemeter may be ordered with an external output jack that supplies a nominal 100-millivolt signal to a strip chart recorder.

The Bacharach smokemeter (Figure 17) is also a portable, battery-powered unit designed to New Jersey specifications. The instrument consists of a sensor unit containing the light source and optical detector, and a readout box containing operating controls, meter, electronic circuitry, and power supply. The light source is a GE No. 502 incandescent bulb, while the optical detector is a cadmium sulfide photocell. Batteries can be recharged by plugging them into a 120-volt AC outlet for 12 to 16 hours. Operating controls in the readout unit include an on-off switch, "zero" and "full-scale" adjustments, battery voltage indicator, and a switch that allows the peak opacity reading to be retained. The normal operating mode of the instrument gives continuous opacity readings. The smokemeter is equippped with an external output jack that supplies up to 377 millivolts to a recorder. An interesting feature of the Bacharach instrument is the grid network in the sensor head (Figure 18). The purpose of this "eggcrate" is to straighten the exhaust plume and create a pressure drop that is supposed to sweep air over the optical lens system.

The Nebetco smokemeter (Figure 19) was also designed to meet New Jersey specifications. The instrument can be used with either a rechargeable battery power source or 120-volt AC power. There is a separate readout box for each power source, with the battery-powered configuration being the most portable. Both readout boxes have an alarm that sounds when a predetermined opacity level is exceeded, as well as the usual on-off switch, "zero" and "full-scale" adjustments, and meter. The 120-volt readout box will supply 64 millivolts externally for a recorder. The design point where the Nebetco smokemeter differs most from the Atlantic Research and Bacharach instruments is in the optical system. The Nebetco system has the light source and photocell in a single housing on one side of the sensor unit, or "cage", and a focusing lens and reflector on the other side. The light beam passes throug a semi-transparent mirror and is focused by the lens onto the reflector, which reflects the light back through the lens to the mirror. The light beam is reflected off the mirror and onto the photocell. Calibration of the instrument is accomplished by placing apertures of various diameters in the light beam, thus reducing the amount of light reaching the photocell. The calibration opacity is proportional to the area of the aperture. A complete set of apertures, for 0- to 90-percent opacity in ten-percent opacity increments, was included with the smokemeter.

The three smokemeters are shown in Figure 20 as they might be used to perform a brief inspection smoke test on a diesel-powered truck-tractor.

B. Smokemeter Bench Tests

Each smokemeter, including the PHS instrument, was subjected to a series of bench tests. These tests, which were approved in advance by the Project Officer, were taken principally from the Coordinating Research Council report, "Recommended Evaluation Procedure for Full-Flow, Light-Extinction Smokemeters." The following is a brief summary of the tests selected and their objective.

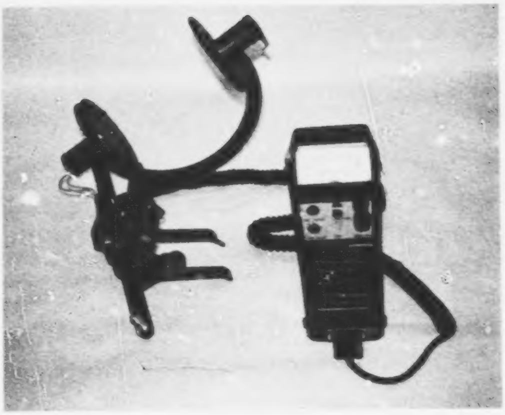


FIGURE 16. ATLANTIC RESEARCH OPACITY METER

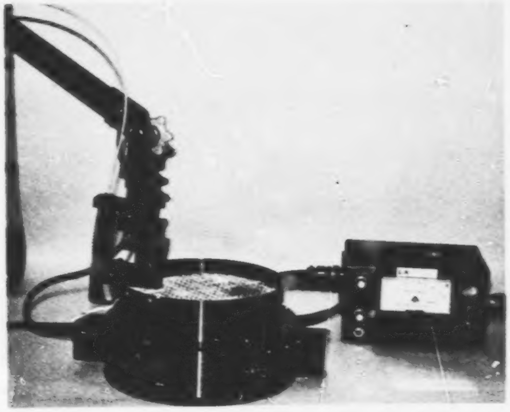


FIGURE 17. BACHARACH OPACITY METER

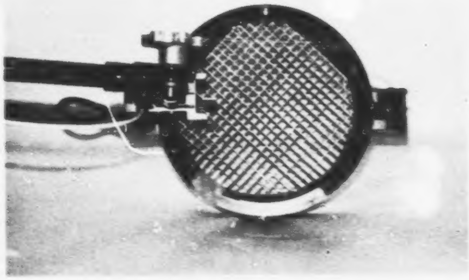


FIGURE 18. GRID NETWORK IN UNIT OF BACHARACH OPACITY METER

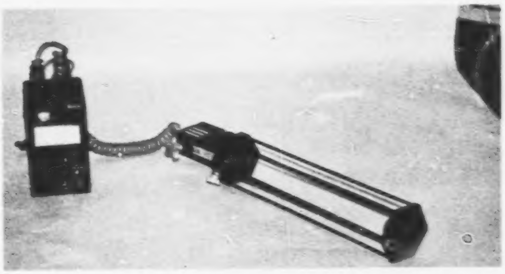
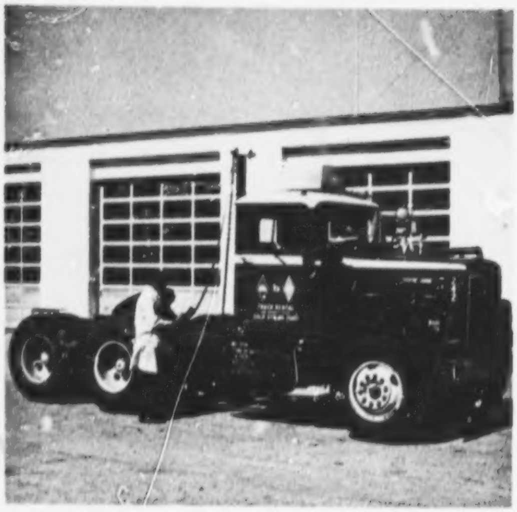
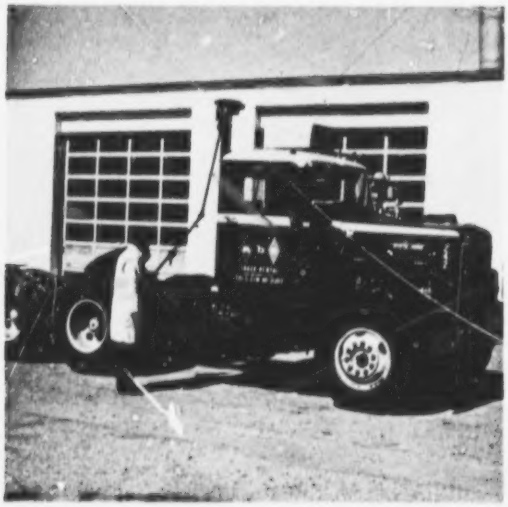


FIGURE 19. NEBETCO OPACITY METER BATTERY POWER PACK CONFIGURATION





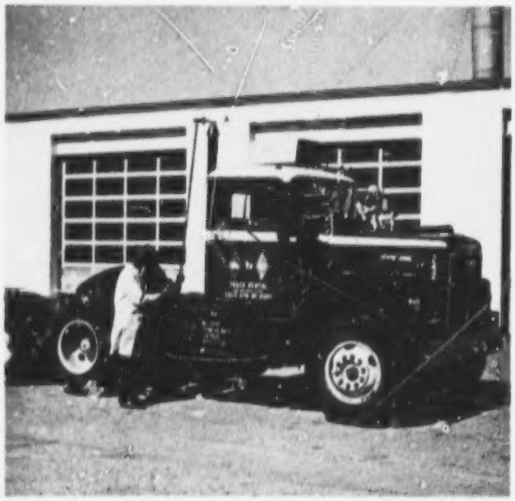


FIGURE 20. ATLANTIC RESEARCH (TOP), BACHARACH (MIDDLE), AND NEBETCO (BOTTOM) SMOKEMETERS IN USE ON A DIESEL-POWERED TRUCK-TRACTOR

(1) Determine the accuracy and linearity of the smokemeter using a set of neutral density filters. For this test, seven filters ranging from 15.5- to 86.0- percent opacity were selected These filters have been calibrated and their values established to a high degree of accuracy.

(2) Determine the zero drift of the smokemeter over a one-hour period.

(3) Determine the sensitivity of the smokemeter to ambient light. A 125-watt spotlight was directed into the photocell and light source openings from different angles. Also, a white reflecting surface was used to reflect the light into the photocell. This simulates a plume of white smoke passing through the smokemeter.

(4) Determine the sensitivity of the smokemeter to ambient temperatures. Each smokemeter was placed in a temperature chamber and soaked at 75, 100, 125, and 150 degrees F. The change in the smokemeter's zero, half-scale, and full-scale settings was measured at each temperature.

(5) Determine the time response of the smokemeter to a rapid change in opacity. Both the CRC procedure and an alternate procedure were used, as questions were raised concerning the efficacy of the CRC procedure.

C. Results of Smokemeter Bench Tests

1. Static Filter Calibration Test - The results of the filter calibration of the PHS smokemeter are given in Table 3. Instrument meter error was quite low, with deviation from the filter value being one-percent opacity, or less. Meter error tended to the high (or plus) side. Figure 21 shows the meter reading and error plotted versus filter value. The smokemeter output at zero and 100- percent opacity was 10 millivolts and zero millivolts, respectively. The theoretical linear output was calculated from these two end points. The observed output, which was measured on a digital voltmeter, agreed closely with the theoretical output. Hence the linearity error, which expresses the difference between observed and theoretical outputs as a percentage of the total net output, was very low. Note that a meter error on the high (or plus) side yields a linearity error on the low (or minus) side, and vice versa. Figure 22 shows the output voltage and linearity error as functions of filter opacity. The equations for the meter error, theoretical linear millivolts, and linearity error appear at the bottom of Table 7.

TABLE 3. CALIBRATION DATA FOR PHS SMOKEMETER END-OF STACK

O_F Filter Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	10.0 (=Vc)	10.0	0
100	100*	0	0 (=Vo)	0	0
15.5	15.3	-0.2	8.47	8.45	+0.2
22.5	23.0	+0.5	7.70	7.75	-0.5
37.5	38.3	+0.8	6.17	6.25	-0.8
49.5	50.0	+0.5	5.00	5.05	-0.5
61.0	62.0	+1.0	3.80	3.90	-1.0
73.0	74.0	+1.0	2.60	2.70	-1.0
86.0	86.4	+0.4	1.36	1.40	-0.4
Opaque	100.0	0	0	0	0
Clear	0	0	10.0	10.0	0

*Meter adjusted to these values.

TABLE 4. CALIBRATION DATA FOR ATLANTIC RESEARCH MODEL 101 SMOKEMETER

O_F Filter Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	105.4 (=Vc)	105.4	0
100	100*	0	24.2 (=Vo)	24.2	0
15.5	15.8	+0.3	92.8	92.8	0
22.5	24.5	+2.0	85.6	87.1	-1.8
37.5	41.0	+3.5	70.6	75.0	-5.4
49.5	48.8	-0.7	65.2	65.2	0
61.0	64.5	+3.5	52.8	55.9	-3.8
73.0	71.2	-1.8	46.8	46.1	+0.9
86.0	86.5	-0.5	35.0	35.6	-0.7
Opaque	100.0	0	24.2	24.2	0
Clear	0	0	105.4	105.4	0

*Meter adjusted to these values.

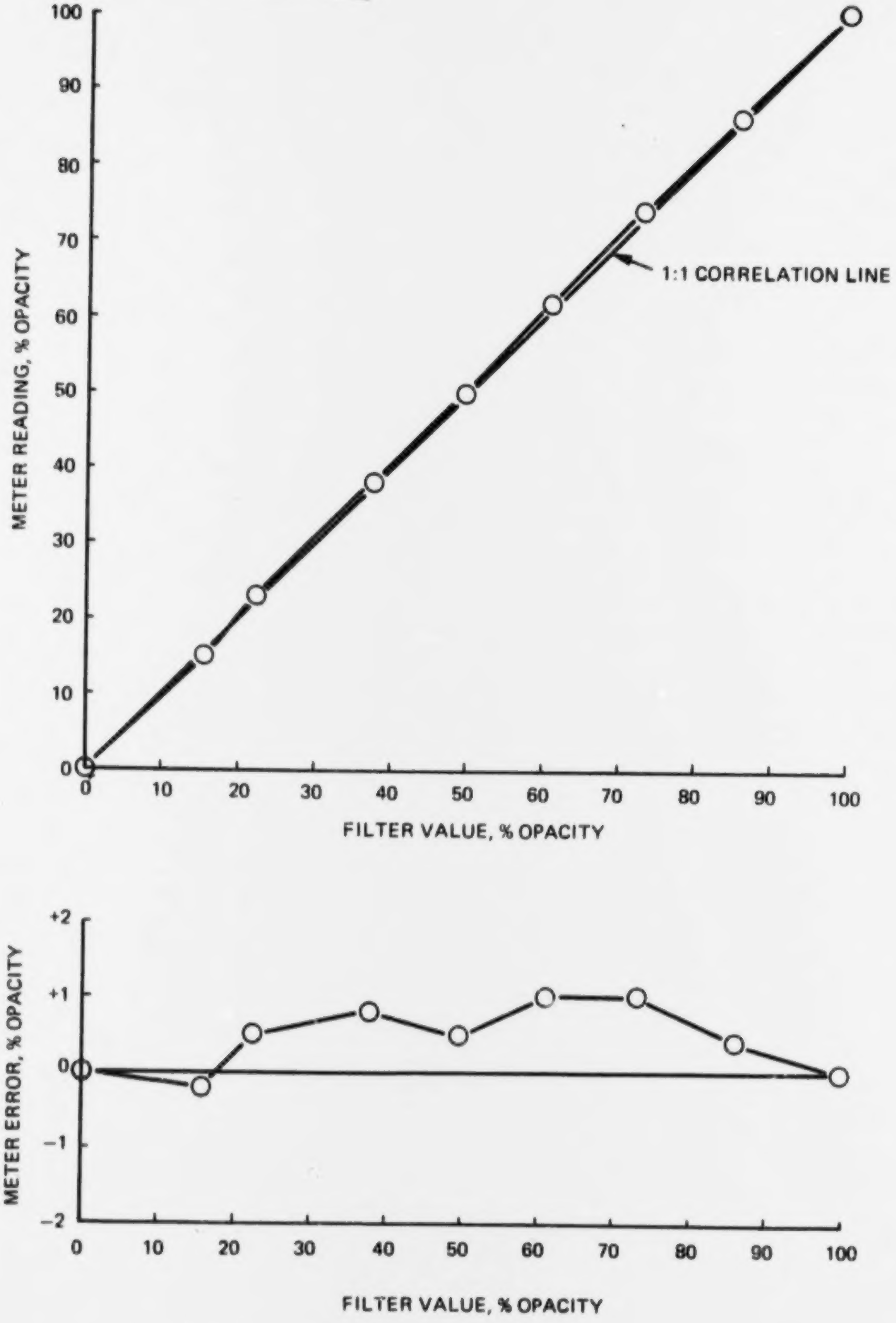


FIGURE 21. METER READING AND ERROR OF PHS SMOKEMETER

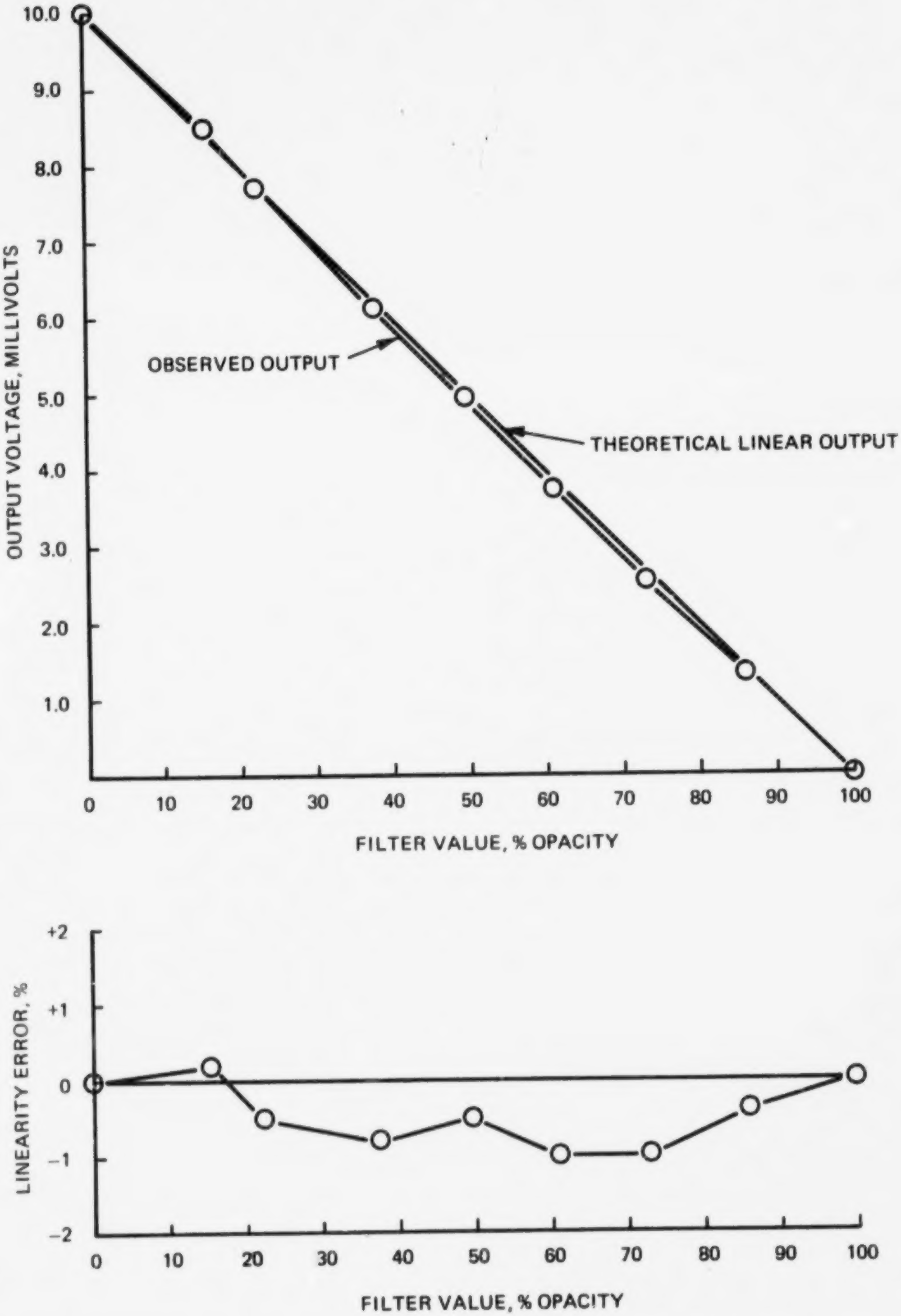


FIGURE 22. OUTPUT VOLTAGE AND LINEARITY ERROR OF PHS SMOKEMETER

The Atlantic Research smokemeter had more meter error than the PHS instrument. Maximum meter error was 3.5- percent opacity high (Table 4). Meter error was predominantly on the high side, though the instrument did read low at two points. Figure 23 shows meter reading and error as functions of filter opacity. Smokemeter output at zero opacity was 105.4 mv. At 100- percent opacity there was a residual voltage of 24.2 mv; i.e., the output did not drop to zero when no light fell on the photodiode. The observed mv output and linearity error are shown in Figure 24. Linearity error was, of course, greater for the Atlantic Research instrument than for the PHS unit.

The Bacharach smokemeter read low throughout the range of filter opacities. In general, meter error increased with filter opacity (Table 5). The meter reading and error are shown in Figure 25. When instrument output was measured, it was found that there was less output (2 mv) at zero opacity than at 100- percent opacity (356 mv). This is opposite from the output situation of the PHS smokemeter, which increases its output as light intensity on the photocell increases. However, the Bacharach instrument uses a photoresistive light detector instead of the photo-voltaic detector used in the PHS unit. Hence, when more light falls on the Bacharach photocell, the resistance in the meter (or recorder) circuit increases and voltage output decreases. In any case, the observed output differed considerably from the theoretical linear output, and the linearity error was greater than that of the PHS and Atlantic Research units. Figure 26 shows the output and resulting error of the Bacharach instrument.

The Nebetco smokemeter could not be checked for accuracy in the usual manner, as neutral density filters produced completely erroneous meter readings. In general, meter opacity was from one-third to two-thirds the value of the filter. However, the apertures intended for calibration of this instrument produced meter readings close to their specified value.

It should be noted that the other smokemeters under consideration are calibrated by absorption of the light beam by a medium, i.e., a neutral density filter. The Nebetco instrument, however, is calibrated by reducing light beam intensity by an aperture in the light path. The important difference in these two methods of calibration is that use of a neutral density filter approximates what a light-extinction smokemeter (and the eye) sees in actual opacity measurement, while the reduction of light intensity by an aperture does not.

When the smokemeter was calibrated with the reference apertures, meter readings (Table 6) were low throughout the opacity range (10- to 90- percent opacity). The meter readings and error for the Nebetco instrument with the 120- volt power supply are plotted

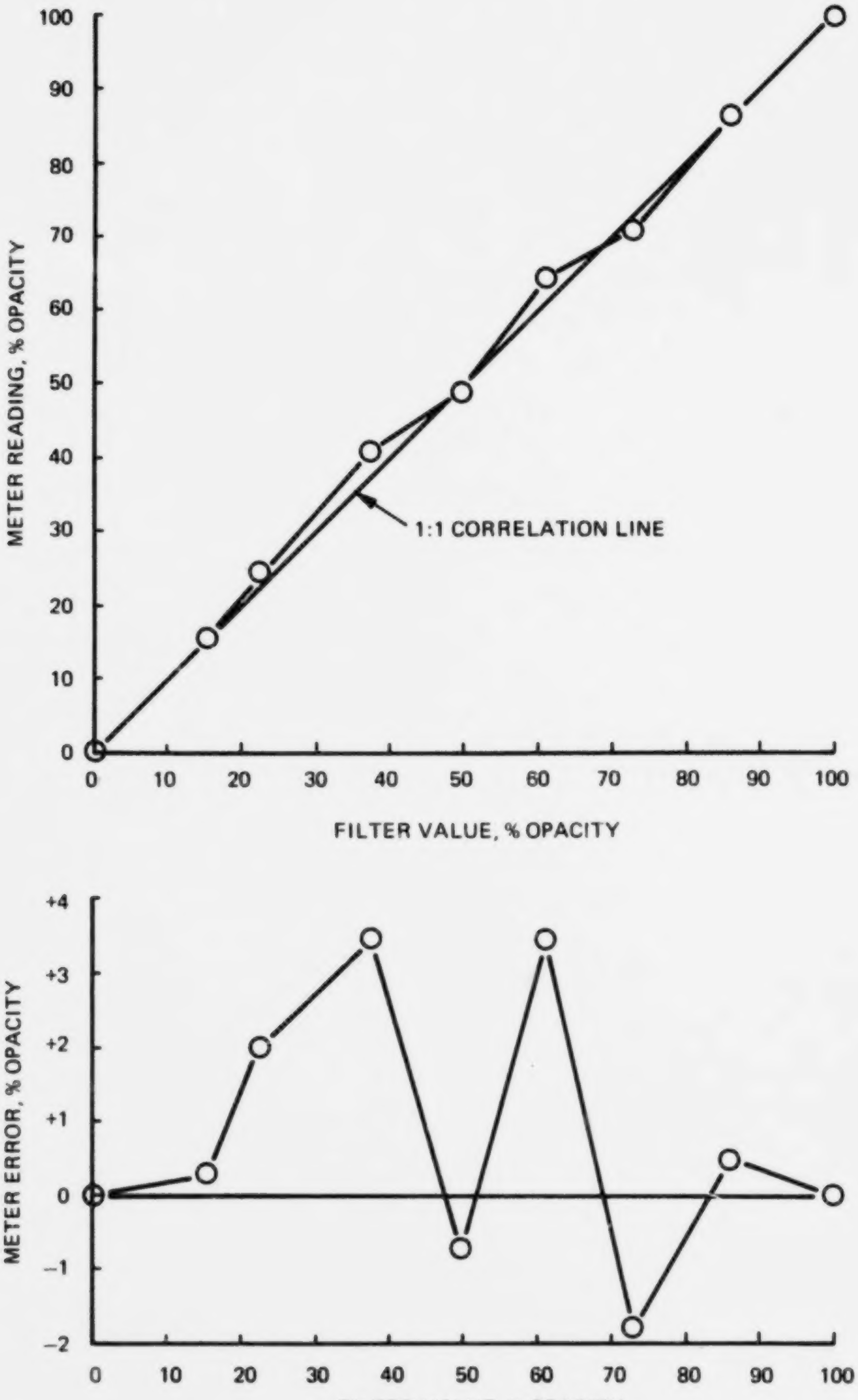


FIGURE 23. METER READING AND ERROR OF ATLANTIC RESEARCH SMOKEMETER

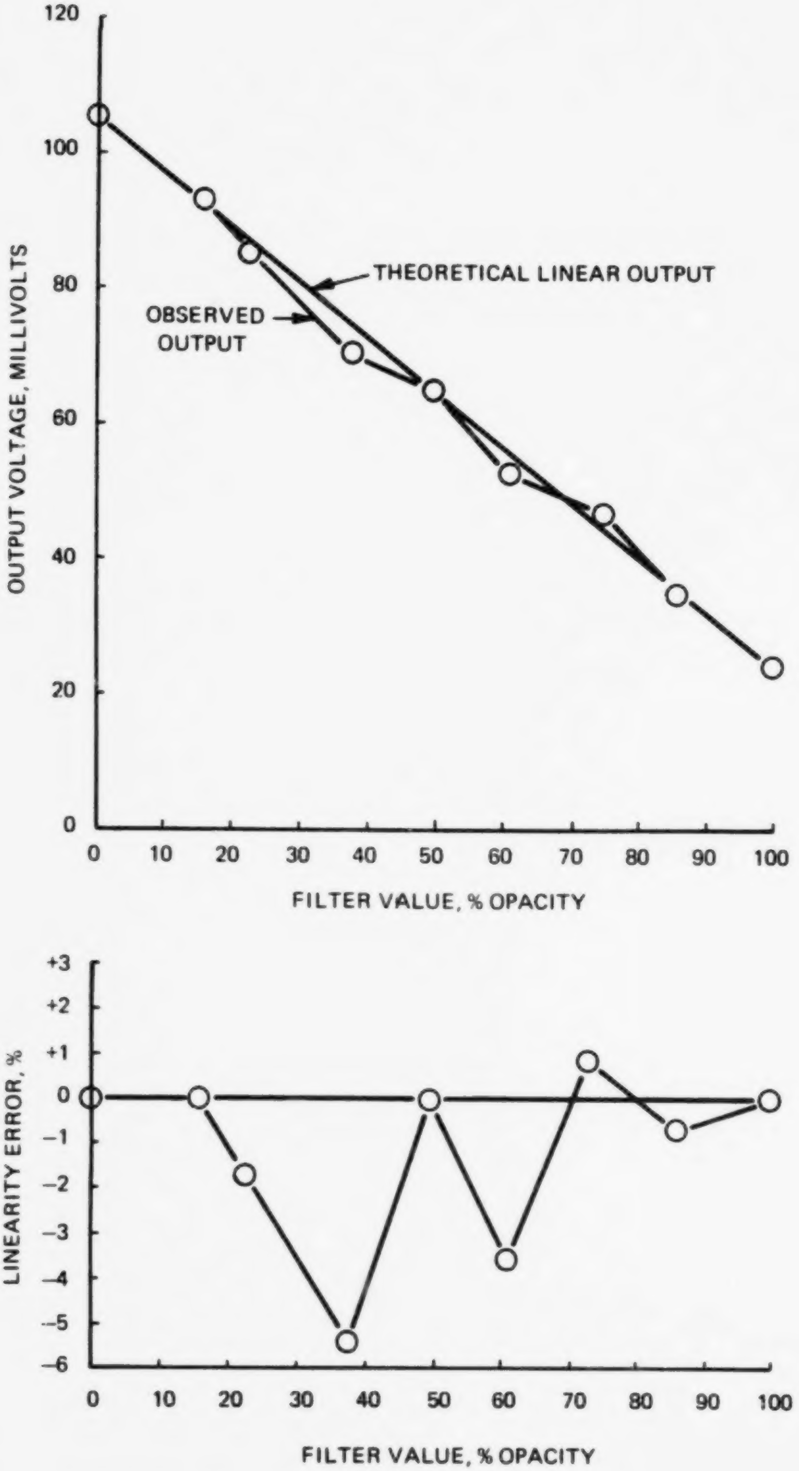


FIGURE 24. OUTPUT VOLTAGE AND LINEARITY ERROR OF ATLANTIC RESEARCH SMOKEMETER

TABLE 5. CALIBRATION DATA FOR BACHARACH MODEL 73-7004 SMOKEMETER

O_F Filter Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	2.0 (=Vc)	2.0	0
100	100*	0	356.0 (=Vo)	356.0	0
15.5	14.7	-0.8	50.0	56.9	1.9
22.5	19.7	-2.8	67.0	81.6	4.1
37.5	33.4	-4.1	115.0	134.8	5.6
49.5	46.5	-3.0	152.0	177.2	7.1
61.0	58.0	-3.0	194.0	217.9	6.7
73.0	67.5	-5.5	231.0	260.4	8.3
86.0	80.0	-6.0	277.0	306.4	8.3
Opaque	100.0	0	356.0	356.0	0
Clear	0	0	2.0	2.0	0

*Meter adjusted to these values.

TABLE 6. CALIBRATION DATA FOR NEBETCO MODEL NLT-1DE SMOKEMETER WITH MODEL EM-3 POWER SOURCE

O_F Filter Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	3.0 (=Vc)	3.0	0
100	100*	0	64.0 (=Vo)	64.0	0
10.0	8.0	-2.0	3.5	9.1	9.2
20.0	18.0	-2.0	6.5	15.2	14.3
30.0	26.0	-4.0	10.0	21.3	18.5
40.0	36.0	-4.0	14.5	27.4	21.1
50.0	45.5	-4.5	19.0	33.5	23.8
60.0	54.0	-6.0	24.0	39.6	25.6
70.0	64.5	-5.5	30.5	45.7	24.9
80.0	75.0	-5.0	41.5	51.8	16.9
90.0	89.0	-1.0	51.0	57.9	11.3
Opaque	100.0	0	64.0	64.0	0
Clear	0	0	3.0	3.0	0

*Meter adjusted to these values.

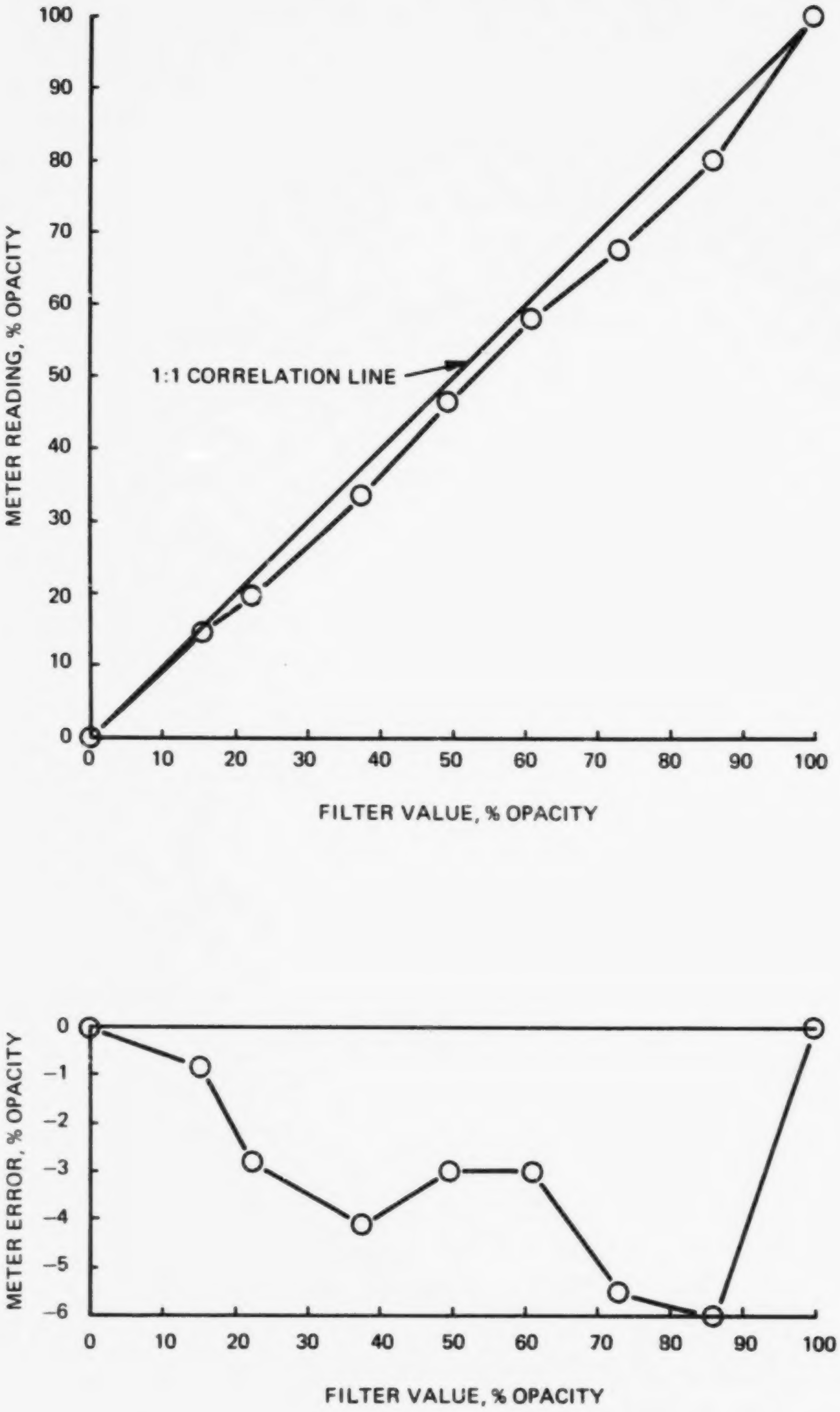


FIGURE 25. METER READING AND ERROR OF BACHARACH SMOKEMETER

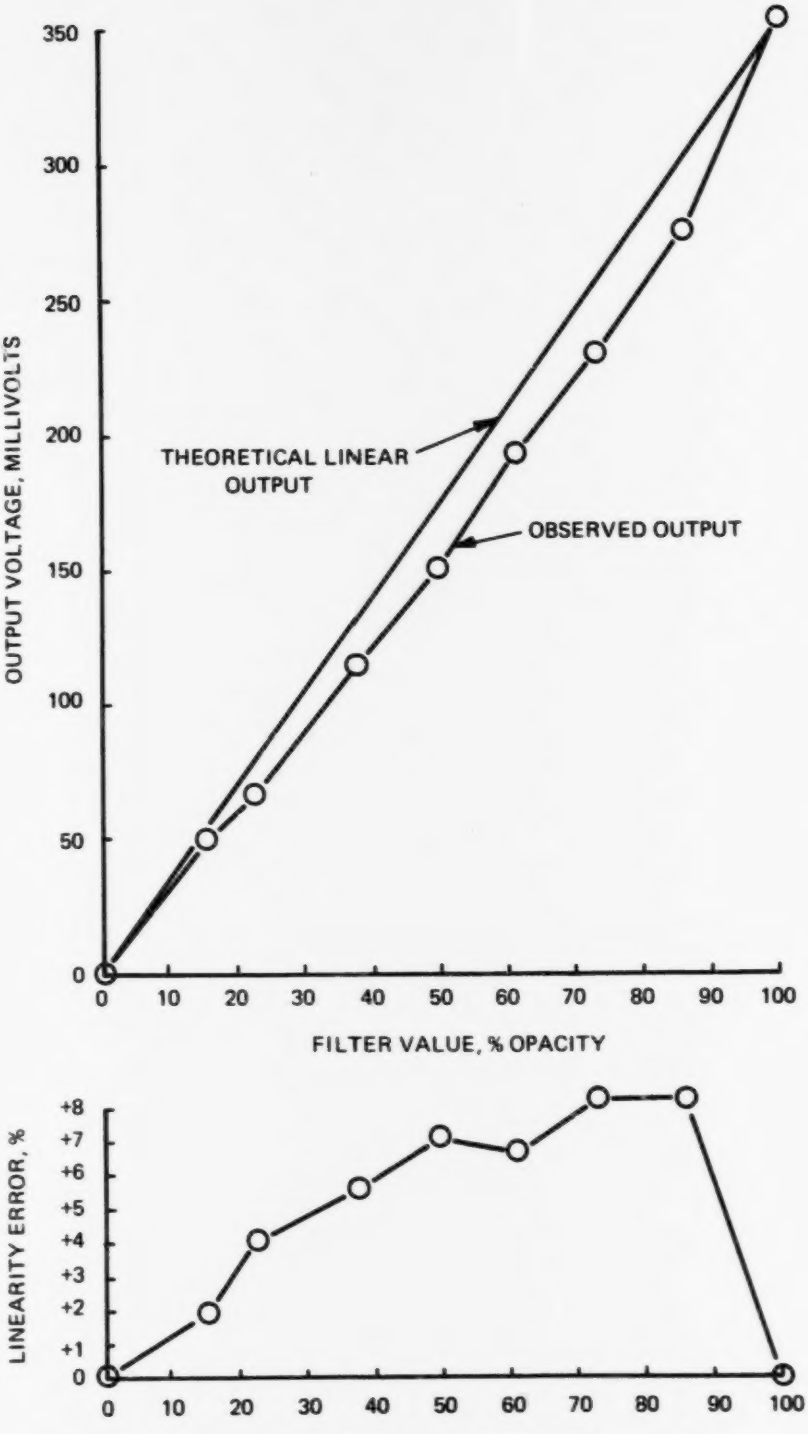


FIGURE 26. OUTPUT VOLTAGE AND LINEARITY ERROR OF BACHARACH SMOKEMETER

in Figure 27. There was a rather large discrepancy between the observed output and the calculated linear output; in fact, the discrepancy was much greater than the difference between meter reading and aperture value would normally imply. The reason for this anomaly is not known. The output voltage and linearity error are shown in Figure 28. Note how the linearity error falls off rapidly above 70- percent opacity.

The Nebetco Smokemeter with the portable battery power supply was also briefly checked for accuracy. This configuration produced good agreement between meter readings and aperture value. However, output voltage could not be measured, as the portable unit has no provision for external output. The meter readings are given in Table 7. An attempt to calibrate the smokemeter with neutral density filters again produced very low meter readings.

In summary, the PHS smokemeter had the highest degree of calibration accuracy, followed by the Atlantic Research and Bacharach instruments. The 120-volt Nebetco unit, though not calibrated with neutral density filters, was about as accurate as the Bacharach. The portable Nebetco was especially accurate up to 70- percent opacity. However, it is difficult to directly compare the Nebetco with the other smokemeters, due to the very different methods of calibration.

2. Zero Drift- The zero drift of the four smokemeters is given below:

Elapsed Time, Minutes	Zero Drift, % of Chart			
	PHS	A.R.	Bacharach	Nebetco
5	0	+0.2	0	0
10	+0.2	+0.2	0	0
15	+0.2	0	+0.2	0
20	+0.2	0	+0.4	0
30	+0.2	0	+0.8	0
45	+0.3	-0.2	+1.0	0
60	+0.3	-0.2	+3.0	0
Maximum Drift	+0.3	±0.2	+3.0	0

Hence, the Bacharach instrument showed the greatest drift over the one-hour period, and the Nebetco the least. However, none of the drifts exhibited by the instruments was considered excessive, especially for the first 45 minutes. At the end of the one-hour period the full-scale (opaque) settings were checked. The Bacharach and Nebetco instruments decreased one percent of scale, while the PHS and Atlantic Research units showed no change.

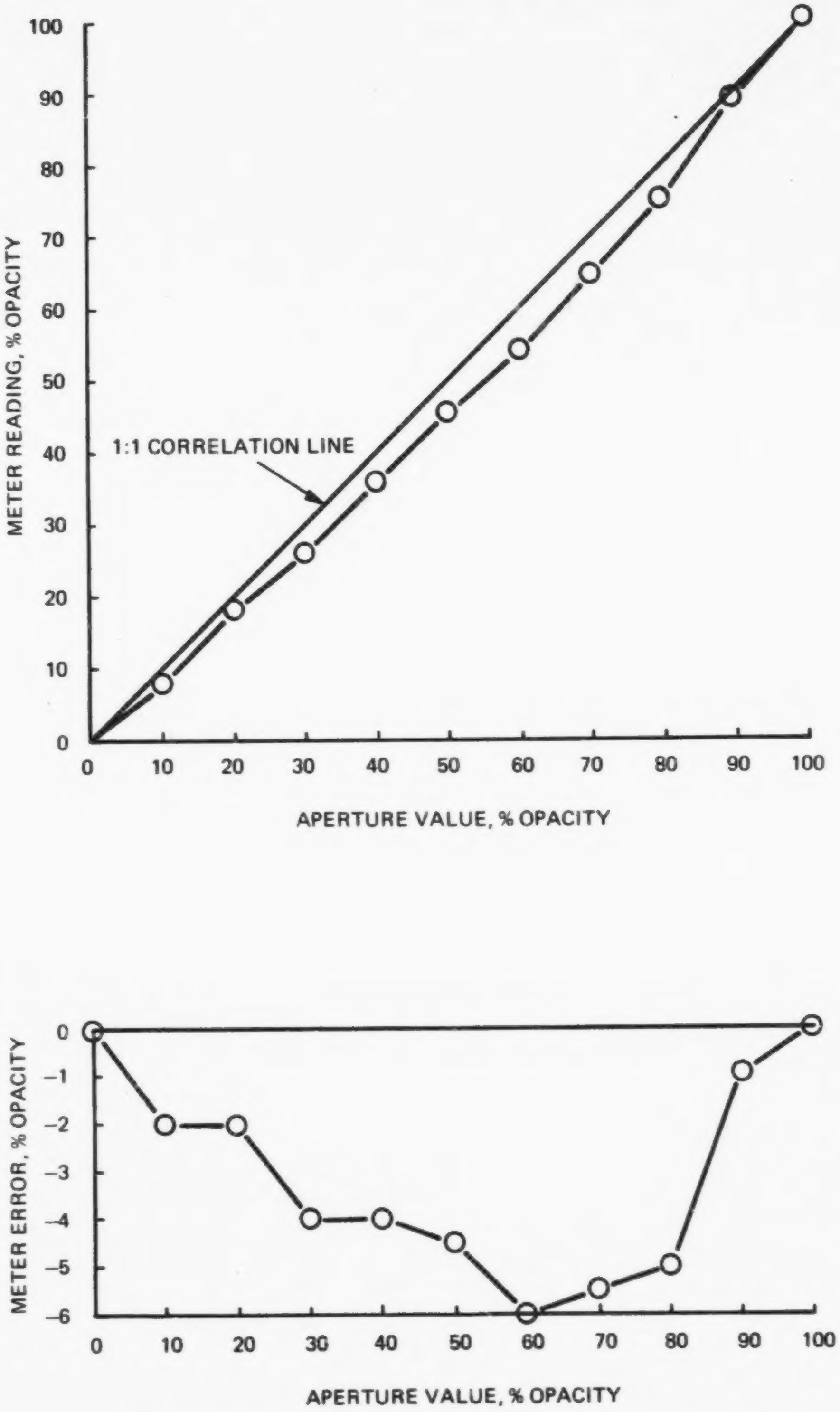


FIGURE 27. METER READING AND ERROR OF NEBETCO SMOKEMETER

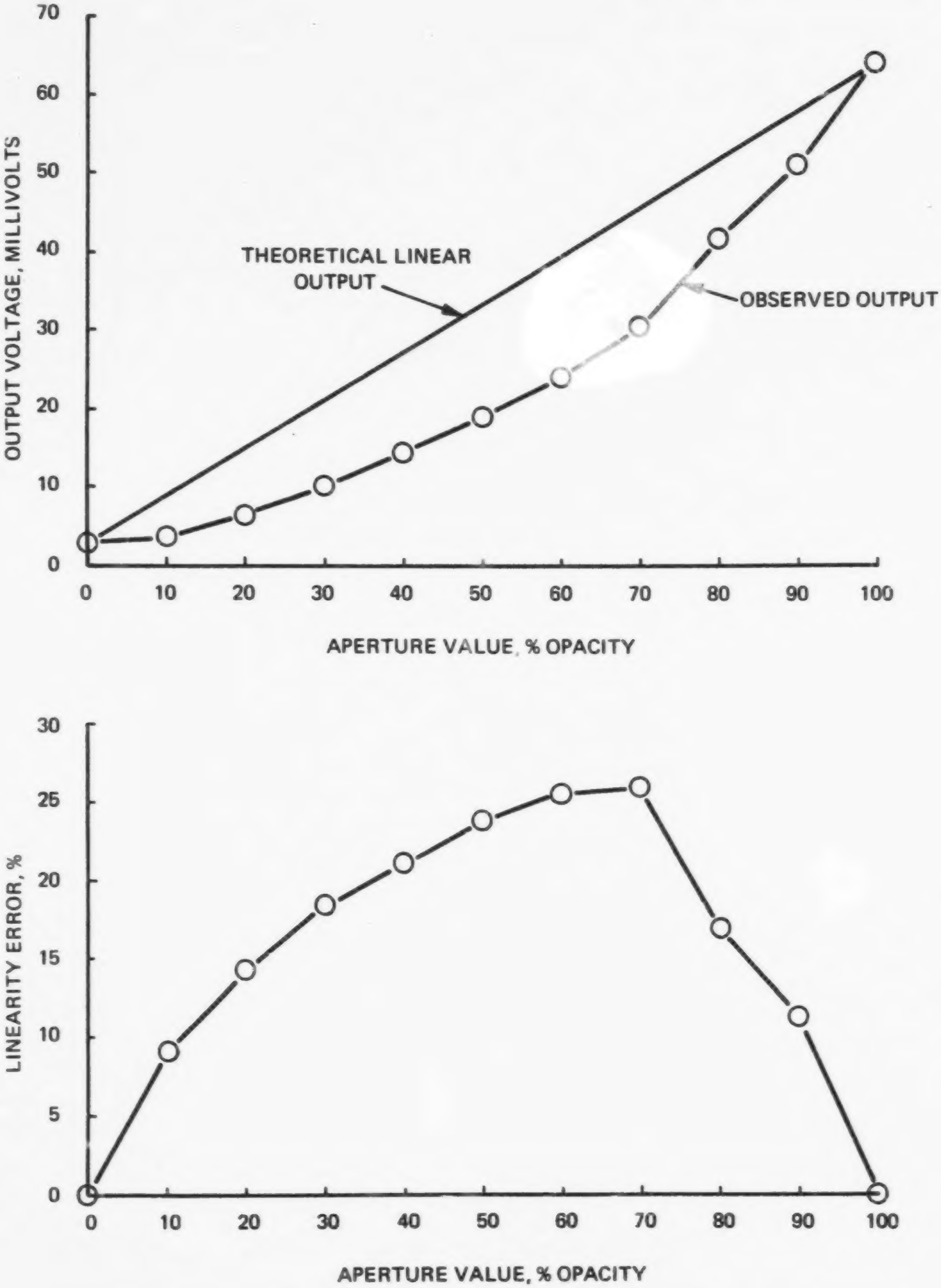


FIGURE 28. OUTPUT VOLTAGE AND LINEARITY ERROR OF NEBETCO SMOKEMETER

TABLE 7. CALIBRATION DATA FOR NEBETCO MODEL NLT-1DE SMOKEMETER WITH MODEL BM-1 POWER SOURCE

O_F Aperture Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	No Output Data with BM-1 Power Source	N.A.	N.A.
100	100*	0			
10.0	10.0	0			
20.0	20.0	0			
30.0	29.0	-1.0			
40.0	39.0	-1.0			
50.0	50.0	0			
60.0	60.0	0			
70.0	73.0	+3.0			
80.0	83.0	+3.0			
90.0	94.0	+4.0			
Opaque	100.0	0			
Clear	1.5	1.5			

*Meter adjusted to these values.

Equations used to find quantities E_M, V_F, and E_L:

(1) $E_M = O_M - O_F$

(2) $V_F = \frac{Vc - Vo}{100}(100 - O_F) + Vo$

(3) $E_L = \frac{100}{Vc - Vo}(V_M - V_F)$

3. Effect of Ambient Light- Changes in each smokemeter's zero and half-scale settings were measured when a 125-watt spotlight was directed at the photocell and light source openings from various angles. The light was aimed directly into these openings and also reflected off a white reflecting surface into the photocell. The angles of light incidence were 90, 75, 60, 45, 30, 15 and 0 degrees. The manner in which these angles were defined is illustrated in Figure 29 (a). The spotlight was also held at a constant angle of inclination as it was moved through the various incident angles. This angle of inclination shown in Figure 29 (b), was the minimum allowed by the shape of the smokemeter's optical unit.

The test procedure consisted of adjusting a smokemeter to zero or 50- percent opacity, then shining the spotlight into the openings or onto the reflector. When measuring the change in zero setting, a strip chart recorder was used instead of the instrument meter. The recorder gain control was set so that the zero occurred at midpoint of the chart. The spotlight was moved in a half circle from 90 degrees right to 0 degrees, and then to 90 degrees left. Equal right and left incident angles produced nearly identical changes in the smokemeter settings. The data in Table 8 are the average of the changes resulting from identical right and left incident angles.

From the data in Table 8, it can be seen that the effect, if any, of the ambient light was a reduction in the instrument setting. This was expected, of course, as the ambient light effectively raises the transmittance of light to the photocell and hence lowers the measured opacity (even if it is zero opacity). Note also that the changes produced when the light was reflected into the photocell were greater than those that occurred when the light shone directly into the opening. This was also expected, since the reflected light enters the photocell in virtually the same plane as that from the light source.

The changes in the smokemeter's zero settings, graphed in Figure 30, show that the Atlantic Research instrument was almost completely insensitive to the ambient light. The PHS instrument was only slightly affected, and then just at the two smallest incident angles. The Bacharach was light sensitive at angles from zero to 45 degrees and showed larger changes in its zero reading than the PHS unit. The Nebetco smokemeter was very sensitive to light. Any incident angle up to 60 degrees produced a change in the instrument's zero setting.

Changes in the instrument's half-scale settings (Figure 31) follow the same general trend as the zero changes. This trend can be seen by comparing Figures 30 and 31. The Atlantic Research smokemeter again proved to be almost insensitive to the ambient

TABLE 8. EFFECT OF AMBIENT LIGHT ON SMOKEMETER ZERO AND HALF-SCALE

Light Incident Angle, degrees	Zero Change, % Opacity							
	PHS		Atlantic Res.		Bacharach		Nebetco	
	Direct	Refl.	Direct	Refl.	Direct	Refl.	Direct	Refl.
90	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	-0.5	-2.0
45	0	0	0	0	0	-2.0	-1.5	-3.5
30	0	0	0	0	-1.5	-3.0	-2.0	-5.0
15	-0.5	-1.0	0	0	-3.0	-4.5	-4.0	-6.0
0	-2.0	-2.5	0	-0.5	-4.5	-5.5	-7.0	-7.0

Light Incident Angle, degrees	Half-Scale Change, % Opacity							
	PHS		Atlantic Res.		Bacharach		Nebetco	
	Direct	Refl.	Direct	Refl.	Direct	Refl.	Direct	Refl.
90	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	-1.5
60	0	0	0	0	-0.5	-1.5	-1.0	-3.5
45	0	0	0	0	-0.5	-3.2	-1.5	-4.5
30	0	0	0	0	-1.0	-5.0	-2.5	-5.5
15	-0.2	-0.5	0	0	-1.5	-6.0	-4.0	-6.5
0	-0.5	-1.0	0	-0.5	-3.5	-7.0	-6.0	-7.5

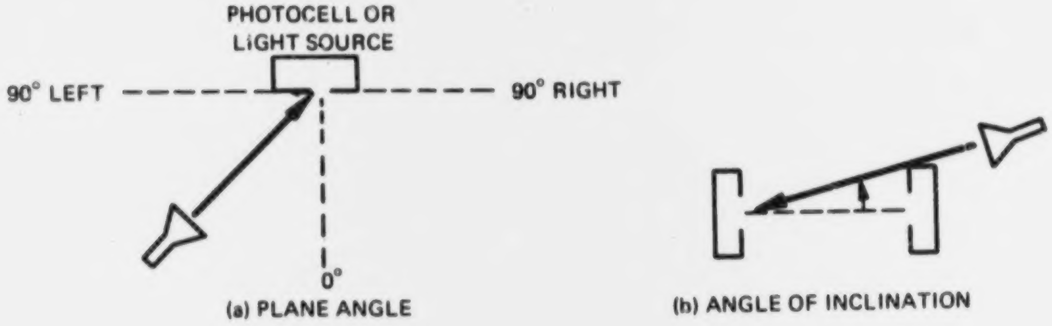

PHOTOCELL OR
LIGHT SOURCE
90° LEFT
90° RIGHT
0°
(a) PLANE ANGLE
(b) ANGLE OF INCLINATION

FIGURE 29. ANGLES OF LIGHT INCIDENCE

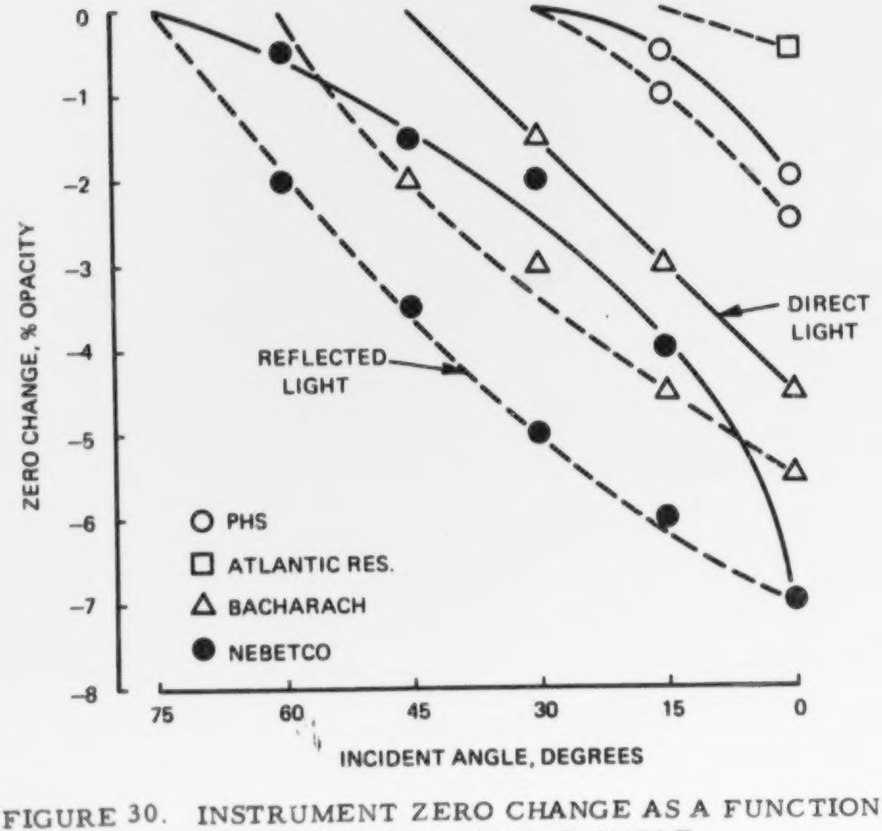


FIGURE 30. INSTRUMENT ZERO CHANGE AS A FUNCTION OF AMBIENT LIGHT INCIDENT ANGLE

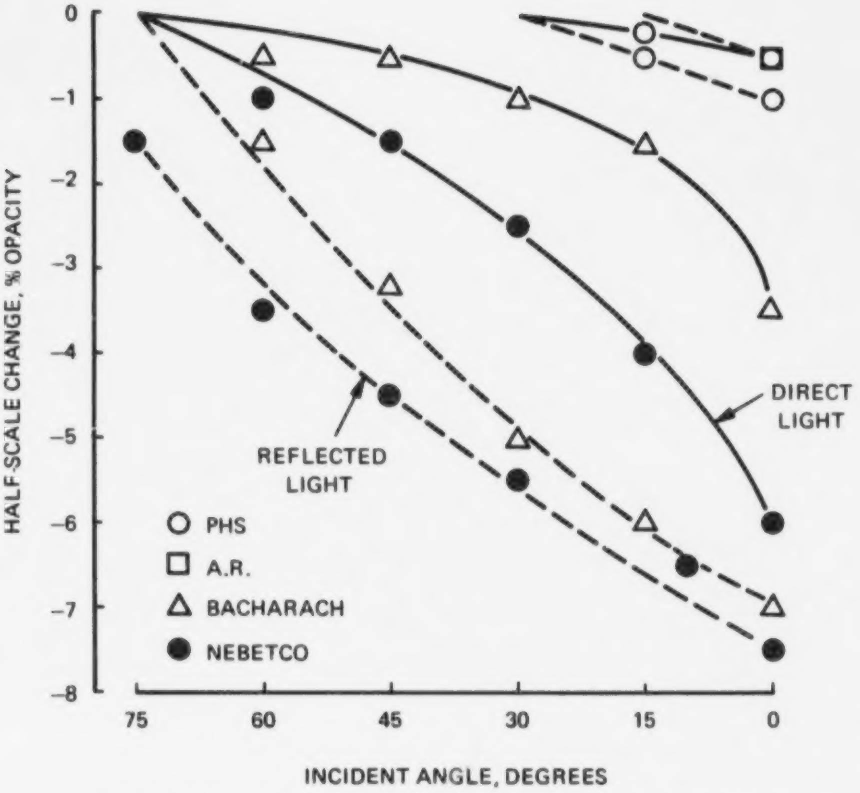


FIGURE 31. INSTRUMENT HALF-SCALE CHANGE AS A FUNCTION OF AMBIENT LIGHT INCIDENT ANGLE

light, as did the PHS unit. The Bacharach and Nebetco units showed slight increases in incident angle sensitivity at the half-scale setting.

Next, the light was directed at the light source opening, and the change in an instrument's zero setting noted. The Atlantic Research and PHS instruments showed no change whatsoever. The Bacharach had changes of -0.5, -1.0, and -1.5 percent opacity at incident angles of 30, 15 and 0 degrees, respectively. The Nebetco unit does not have separate detector and light source openings, so the spotlight was aimed at the reflector on the other side of the optical head (see description of Nebetco instrument). This tactic produced virtually the same zero changes as when the ambient light directly entered the combination light source-photocell opening.

In summary, the Atlantic Research instrument had the least sensitivity to ambient light, closely followed by the PHS unit. The Nebetco and Bacharach had much more sensitivity than the other two instruments. In passing, it should be noted that the three commercial smokemeters are intended to be mounted on long extension poles and held above the exhaust stack. It may be possible to turn an instrument so that sunlight, the principal ambient light, is at a 90-degree angle to the smokemeter light beam. This would negate most of the effects of the ambient light, as no instrument showed sensitivity to light from a 90-degree incident angle in this bench test.

4. Effect of Ambient Temperature- Changes in each instruments' zero, half-scale (50- percent opacity) and full-scale settings were measured at temperatures of 75, 100, 125 and 150 degrees F. Test results are given in Table 9. Changes in zero and half-scale settings are graphed in Figures 32 and 33, respectively.

The test procedure consisted of adjusting an instrument to the appropriate zero, half-scale, or full-scale (opaque) setting, at a baseline temperature of 75 degrees F. The smokemeter was then allowed to soak in the heat chamber until equilibrium at the desired temperature was reached. Temperature readings were obtained by one thermocouple at the instrument's photocell and another at a point near the light source. After equilibrium was reached the change in instrument setting was recorded. A typical test involving the four temperatures required about 30 minutes, so that instrument drift with time was not a significant factor in the observed changes. Also, since the entire optical unit was at equilibrium, thermal distortion and any resulting misalignment of the optical system was at a minimum. All tests were run at least twice and the data in Table 9 are the average of these tests.

TABLE 9. EFFECT OF AMBIENT TEMPERATURE ON SMOKEMETER ZERO, HALF-SCALE, AND FULL-SCALE SETTINGS

Ambient Temp., °F	Zero Change, % Opacity			
	PHS	Atlantic Research	Bacharach	Nebetco
75*	0	0	0	0
100	+1.0	+0.5	+2.5	+4.0
125	+3.0	+2.0	-2.0	+6.5
150	+7.0	+5.5	-4.5	+8.0
Ambient Temp., °F	**Half-Scale Change, % Opacity**			
	PHS	Atlantic Research	Bacharach	Nebetco
75*	0	0	0	0
100	+0.2	0	-2.5	+1.5
125	+1.3	-0.5	-6.5	+3.0
150	+4.0	+0.3	-18.5	+5.2
Ambient Temp., °F	**Full-Scale Change, % Opacity**			
	PHS	Atlantic Research	Bacharach	Nebetco
75*	0	0	0	0
100	0	0	-2.0	+0.7
125	0	0	-5.0	+1.0
150	0	0	-13.0	+0.5

*Baseline Setting.

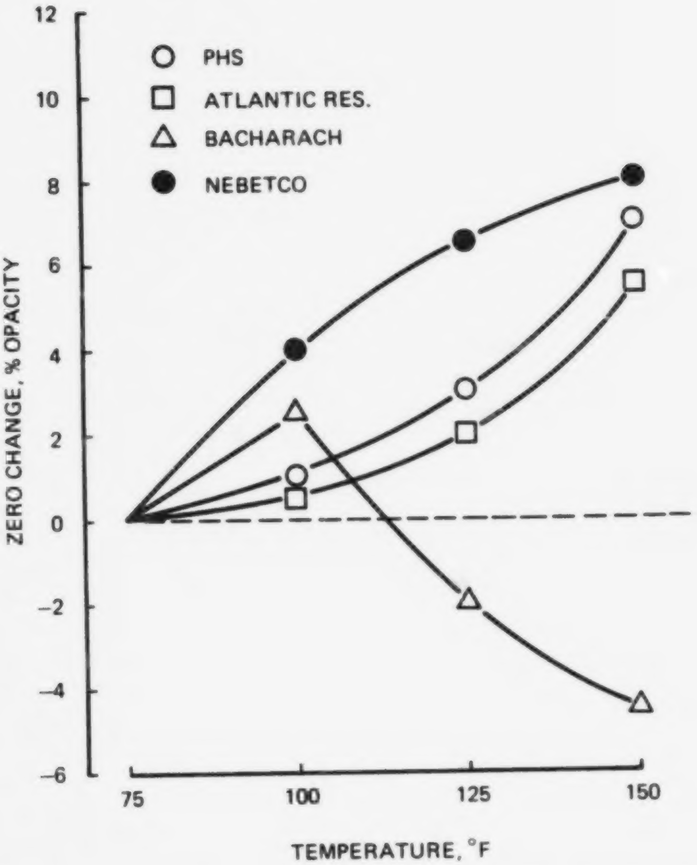


FIGURE 32. INSTRUMENT ZERO CHANGE AS A FUNCTION OF AMBIENT TEMPERATURE

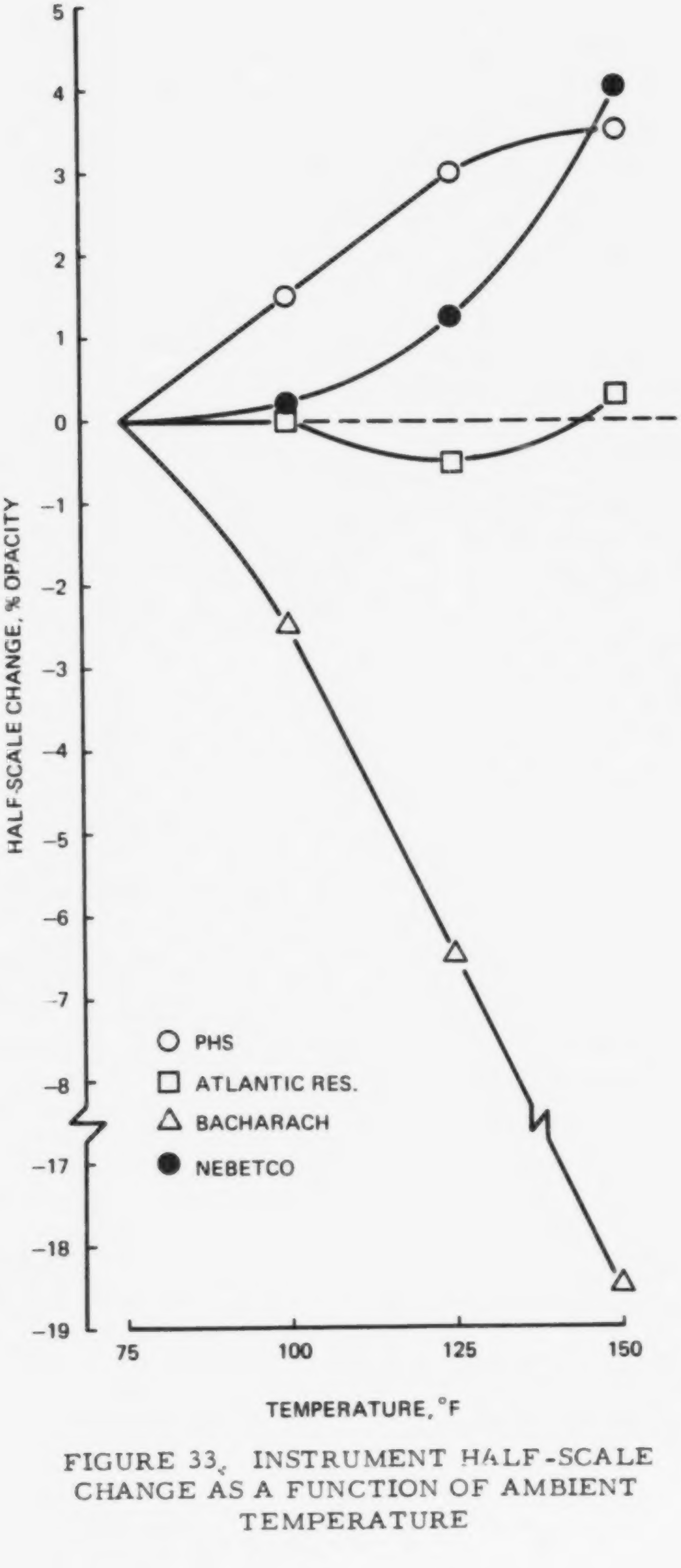


FIGURE 33. INSTRUMENT HALF-SCALE CHANGE AS A FUNCTION OF AMBIENT TEMPERATURE

First, consider the changes in the instruments' zero settings. In general, the smokemeters showed a tendency to increase their zero setting as the temperature increased. The only exception was the Bacharach instrument, which had below-zero readings at 125 and 150 degrees F. The Nebetco instrument showed the largest change at 100 and 125 degrees, while the Atlantic Research had the smallest change. At 150 degrees the Nebetco again had the largest change (8.0 percent above zero), while the Bacharach showed the least change (4.5 percent below zero). Overall, the Atlantic Research instrument was least sensitive to changes in ambient temperature. The Nebetco appeared most sensitive, while the Bacharach and PHS units fell somewhere in the middle.

The changes in half-scale settings were next measured. Again the settings tended to increase with increasing temperature, with the exception of the Bacharach instrument. At all temperatures, the Bacharach registered the greatest changes, the largest a drop of 18.5-percent opacity below half-scale at 150 degrees F. The Atlantic Research instrument was almost completely unaffected by the temperature changes. The PHS and Nebetco units exhibited nominal increases in half-scale opacity which were between those of the other instruments. Note that the changes in half-scale settings show approximately the same trend as the changes in zero settings, though they do not have the same values (compare Figures 32 and 33).

Changes in full-scale setting (opaque light beam path) were significant only for the Bacharach smokemeter. This instrument again showed a decrease from the baseline setting when the ambient temperature was increased. At 150 degrees the drop from baseline reached 13.0- percent of scale. The Nebetco instrument showed very slight increases in the full-scale setting, while the PHS and Atlantic Research units had no detectable changes.

In summary, the Bacharach smokemeter was most affected by increases in ambient temperature, while the Atlantic Research instrument was least affected. The PHS and Nebetco smokemeters showed changes between these two extremes. It should be mentioned that regardless of the change in the instruments' zero, half-scale, or full-scale setting, all of them could be reset by their calibration adjustments. Thus, heat build-up that might occur during a smoke test could be compensated for at the end of the test, but not while the test was in progress. When estimating the effect of temperature on a smokemeter's performance, consideration should therefore be given to the type of smoke test to be run, its duration, the number of tests, and whether the smokemeter can be zeroed and set full-scale between tests. The proximity of the smokemeter to the exhaust pipe is also important. The optical system of the PHS instrument is well removed from the exhaust stack, but the Atlantic Research and Bacharach units are very close to the stack in their normal operation. Therefore, it is more likely that these smokemeters, rather than the PHS, would encounter temperatures similar to those in the bench test.

5. Time Response - The CRC time response test involves the use of a motor-driven chopper to alternately block and clear the smokemeter light beam. The rotational speed of the chopper is adjusted to the maximum that will produce a square wave time-voltage trace on an oscilloscope. Thus, the chopper speed is determined by the response time of the particular smokemeter being tested and is not, in general, the same rotational speed used with other smokemeters.

The doubt previously mentioned concerning the correctness of this procedure centered around the idea that the measured time response might depend on the speed of the chopper. That is, the rate at which the light beam is obscured by the chopper blade may determine the response of the photocell and, hence, the full-scale response time of the smokemeter. Also, since the chopper speed is not usually the same for different model smokemeters, the test procedure is different for every instrument and hence may invalidate the comparison of data for various smokemeters.

In spite of these doubts, a series of CRC tests was performed using a variable speed, motor-driven chopper. An oscilloscope was connected to the smokemeter output terminals, and Polaroid photographs taken of the time-voltage trace thus obtained. The time response data from these tests are given in Table 10, below. Both the build-up (0% - 100%) and decay (100% - 0%) times are shown, and are the average of three tests.

TABLE 10. SMOKEMETER RESPONSE TIME (CRC PROCEDURE)

	Response time, sec.	
Smokemeter	0-100%	100-0%
PHS	0.10	0.10
Atlantic Research	0.43	0.20
Bacharach	0.10	0.40
Nebetco	0.57	0.40

Although no information was available concerning response times of these instruments, it was thought that at least two of them, the PHS and Bacharach, had response times considerably faster than those measured. It was therefore decided to repeat the tests, using a different method of blocking the light beam.

The next series of tests consisted of dropping a wooden sphere of approximately 3 1/2-inch diameter through the light beam and photographing the time-voltage trace displayed on the oscilloscope. (Due to the design of the Nebetco smokemeter, a one-in diameter steel ball bearing was used in lieu of the wooden sphere). In either case, the sphere was dropped from the same height in each test, for each smokemeter. The data obtained with this procedure are presented in Table 11, below. These data are also the average of three repeatable tests.

TABLE 11. SMOKEMETER RESPONSE TIME (MODIFIED PROCEDURE)

Smokemeter	Response Time, sec. 0-100%	Response Time, sec. 100-0%
PHS	0.008	0.008
Atlantic Research	0.150	-
Bacharach	0.020	0.325
Nebetco	0.075*	0.300*

*0-50% of scale

The response times for the PHS, Atlantic Research, and Bacharach smokemeters were reduced--in some cases, greatly reduced-- when measured by the second procedure. The Nebetco smokemeter responded too slowly to achieve full-scale deflection as the sphere passed through the light beam. Hence, the actual full-scale response time for this instrument is somewhere between the times given in Tables 10 and 11. Due to technical problems, apparently in the oscilloscope, no data was taken on the 100%-0% response time of the Atlantic Research smokemeter.

The data in Table 11 are considered to be more accurate than those in Table 10. The times measured by the second test method are more in keeping with the obviously fast response of the PHS, Atlantic Research, and Bacharach instruments. Therefore, on the basis of the Table 11 data, the PHS instrument had the fastest response, followed by the Atlantic Research, Bacharach, and Nebetco, in that order. It should be noted, however, that the most commonly used strip chart recorders have full-scale response times on the order of 0.30 to 0.50 seconds. Hence, although the Atlantic Research and Bacharach smokemeters have response times several times slower than the PHS instrument, they still respond faster than the typical recorder.

A third method of time response measurement was also tried. This procedure consisted of directing a very brief, yet intense, flash of light into each smokemeter's photocell. Two sources of light were used in this test, a high-intensity strobe light and a photographic flash gun. In order to shine the light directly into the photocell, the sources had to be placed in the smokemeter light beam, thus blocking it completely. With the smokemeter registering 100-percent opacity, the light flash was triggered and an attempt made to measure the time response of the smokemeter as the opacity decreased from 100 percent. This time corresponds to the delay (100%-0%) time of the other test procedures.

A fundamental problem was encountered in this procedure; i.e. the light flash from both sources was too brief in time to permit the smoke-meter to deflect full scale, to zero opacity. The flash gun had no adjustment whatever, and the strobe light was adjustable only to the extent that the time between flashes could be varied; however, the duration of each flash was fixed. The typical smokemeter would deflect only five to ten percent of full scale when registering these light flashes. Therefore, it was concluded that this procedure was not feasible in its present form. A strobe light with truly adjustable flash duration might solve the problem mentioned above, but such an instrument was not available.

D. Smoke Tests With Commercial Smokemeters

The Atlantic Research, Bacharach and Nebetco smokemeters, along with the PHS instrument, were used to measure smoke opacity during several series of tests. One series involved a stationary-mounted Cummins NH-220 engine subjected to the Federal smoke compliance test and a sequence of steady-state runs at several engine speed and load points. Another series of tests was conducted with the four truck-tractors and the city bus used to evaluate the smoke test procedures (Section II). The tests performed by these vehicles were the simulated Federal smoke test, the pertinent New Jersey test (either truck lugdown or bus acceleration), the experimental SwRI test procedure, and the former New Jersey free acceleration test.

1. Smoke Tests With Stationary-Mounted Engine

The three commercial smokemeters and the PHS instrument were used to measure smoke opacity of a stationary-mounted Cummins NH-220 engine subjected to the Federal smoke compliance test and a sequence of steady-state runs. The tests were conducted in a back-to-back manner using first the PHS, then one of the commercial smokemeters. All tests performed with a given smokemeter were done on the same day. Four-in diameter exhaust pipe was used for all tests.

a. Federal Smoke Test Results

The Atlantic Research and Bacharach instruments showed moderate-to-large baseline shifts after each test sequence. After the first sequence, baseline change was about 7.0- percent opacity; after the second sequence, it was about 11.0- percent opacity. The cause of these baseline changes was soot deposit on these instruments' optical lenses. In order to determine the effect of the baseline change on opacity readings, two sets of three sequences were performed with these two smokemeters. For the first set, the lenses were not cleaned between sequences, while for the second set, the lenses were cleaned and the instrument zero and full-scale calibration checked between sequences.

Table 12 contains the data for the Federal smoke tests. Note that the PHS data varied from one day to another. The tests were conducted over a two-week period, and there obviously was some change in the smoke produced by the NH-220 engine. However, the PHS and any given smokemeter were run back-to-back for comparison on the same day; hence, there were only small run-to-run variations in the data used for direct comparison.

TABLE 12. FEDERAL SMOKE TEST DATA--
SMOKEMETER EVALUATION

Smokemeter	"a" Factor	"b" Factor
Atlantic Res.*	24.8	30.9
Atlantic Res.**	21.3	28.7
PHS	20.3	28.0
Bacharach*	32.2	37.7
Bacharach**	26.8	32.4
PHS	28.9	33.4
Nebetco	17.6	24.9
PHS	31.6	37.4

*Lenses not cleaned between tests
**Lenses cleaned between tests

From Table 12 it can be seen that the Atlantic Research smokemeter gave moderately higher (3-4 percent opacity) "a" and "b" factors than the PHS instrument when the A.R. lenses were not cleaned between test sequences, and gave only very slightly higher (1.0- percent opacity) factors than PHS when the lenses were cleaned between sequences.

The Bacharach read moderately higher (3-4 percent opacity) than PHS when its lenses were left uncleaned between sequences, and slightly lower (1-2 percent opacity) than the PHS instrument when the lenses were cleaned. The Nebetco smokemeter produced much lower (12-14 percent opacity) "a" and "b" factors than the PHS instrument. Figure 34 illustrates the data in Table 12.

The three commercial smokemeters displayed the same trends when measuring smoke opacity (with lenses clean) as when their calibration was checked with neutral density filters. That is, the Atlantic Research instrument calibrated slightly high; the Bacharach calibrated slightly low. The Nebetco, when calibrated with neutral density filters rather than with the aperatures provided for this purpose, registered opacity values one-third to two-thirds the value of the filter. Thus, the Nebetco instrument cannot be calibrated with either filters or aperatures in the manner necessary for accurate smoke opacity measurement.

b. Steady-State Smoke Measurement Results

The three smokemeters and the PHS unit were next tested on the NH-220 engine operating at various steady-state conditions and using three, four, and five-in diameter exhaust pipes. Engine speeds were 1600 rpm and 2100 rpm, and engine loads were zero load, full load, and approximately one-third and two-thirds of full load. These four load settings produced a wide range of smoke opacities, exhaust flow rates, and exhaust temperatures.

A special test stand was constructed for this series of tests. The stand consisted of four 4-1/2-foot lengths of exhaust pipe (of one diameter) on which were mounted the four smokemeters (Figure 35). A piece of flexible pipe joined the engine exhaust system to one of the four pipes on the test stand.

The test procedure consisted of setting the engine speed and load to the desired condition, allowing a short time for stabilization, and then connecting the flexible pipe to the test stand pipes for the PHS and one of the other smokemeters in the following order: PHS, smokemeter X, PHS, smokemeter X, PHS. Thus, the measurements made with a given commercial smokemeter were bracketed with measurements from the PHS instrument. This test procedure provided a check on the stability of the smoke opacity during the test. It should be mentioned that this stability was very good, usually ±0.5- percent opacity at low smoke levels and ±1.0- percent opacity at higher levels, according to the PHS smokemeter readings. Finally, any instrument that showed more than 1.0- percent opacity baseline (zero) drift was recalibrated before continuing with the tests. Optical lenses were cleaned as needed.

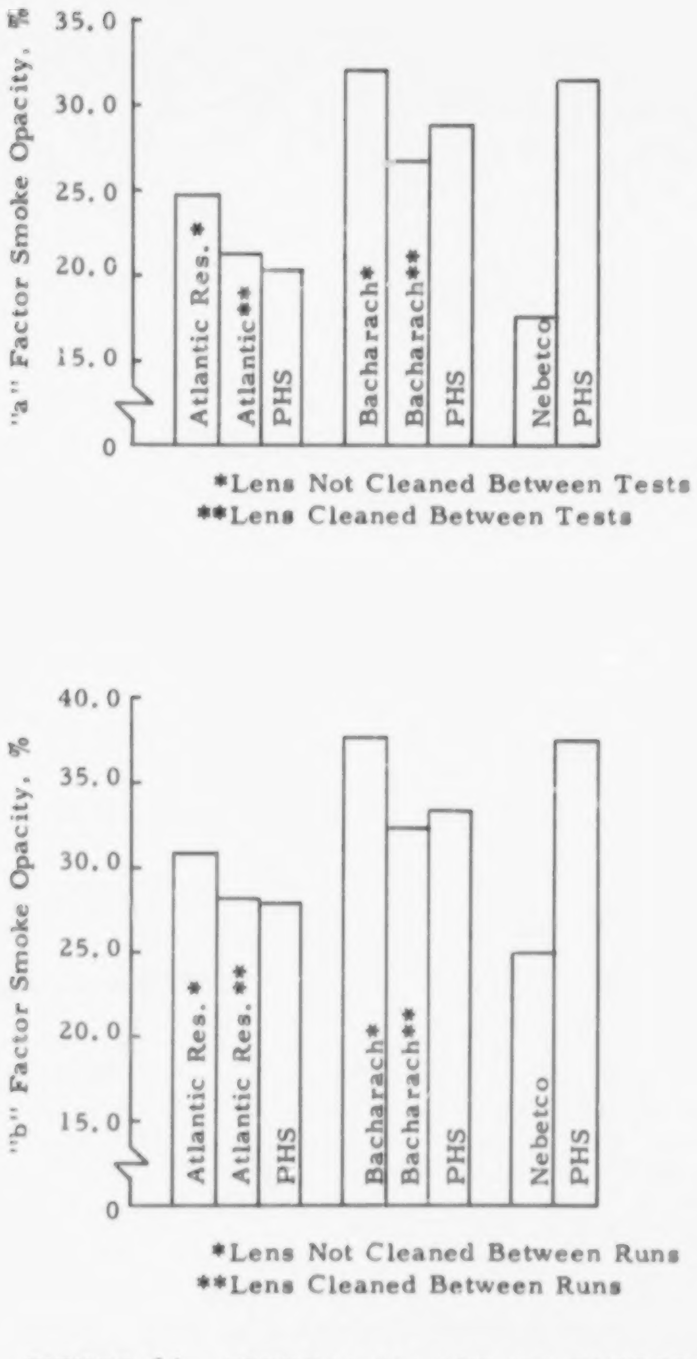


FIGURE 34. FEDERAL "a" AND "b" FACTORS AS MEASURED BY FOUR SMOKEMETERS

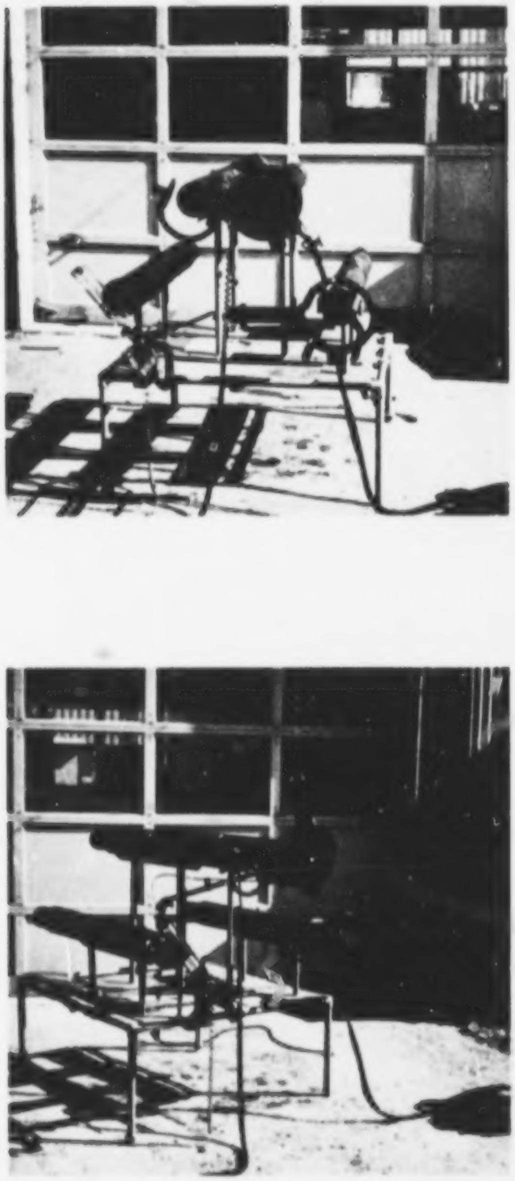


FIGURE 35. TEST STAND WITH FOUR SMOKEMETERS

The data from this series of tests are presented in Table 13. The data are the averages of the individual runs (three runs for the PHS smokemeter, two for all other instruments) made for each engine condition and each pipe size.

At an engine speed of 1600 rpm, and with three-in diameter pipe, the three commercial smokemeters gave lower opacity readings at all engine loads than the PHS instrument. The Bacharach and Atlantic Research instruments were closest to the PHS, and read some 3- to 4- percent opacity low at about 19- to 20- percent opacity (by PHS). The Nebetco smokemeter registered approximately one-half to one-third the opacity of the PHS.

For 1600 rpm and four-in diameter pipe, the Atlantic Research instrument read very close to the PHS until full engine load was reached. At this point the Atlantic Research read about 2.0- percent opacity lower than the PHS. The Bacharach smokemeter read about 1.0- percent opacity higher than the PHS at zero engine load, but agreed very well with PHS at the other opacity levels. The performance of the Nebetco was about the same as with the three-in pipe.

At 1600 rpm and using a five-in diameter pipe, the Atlantic Research smokemeter gave almost exactly the same readings as the PHS instrument. The Bacharach again read slightly higher (about 1.5- percent opacity) than the PHS at zero engine load, but the two instruments agreed very well at higher smoke levels. The Nebetco read close to the PHS at zero engine load, then lapsed into its normal mode of operation at the higher opacity levels.

Engine speed was increased to 2100 rpm and the above tests repeated. On three-in diameter pipe the commercial smokemeters read lower than the PHS instrument by a slightly greater amount than at 1600 rpm. The Bacharach was closest to the PHS, followed by the Atlantic Research and Nebetco.

With four-in pipe and 2100 rpm, the commercial smokemeters again registered lower opacity than the PHS instrument. The Bacharach read very close to PHS opacity at zero and one-third engine load, then registered about 2.5- percent opacity low at the higher smoke levels. The Atlantic Research smokemeter gave readings some 3.5- to 4.5- percent opacity below PHS at these high opacity conditions. The difference between the PHS and Nebetco instruments were again quite large.

For 2100 and five-in pipe the Atlantic Research instrument read slightly lower than PHS opacity at zero and full engine loads, and slightly higher than PHS at one-third load. The Bacharach registered

TABLE 13. STEADY-STATE SMOKE TEST DATA -- SMOKEMETER EVALUATION

Engine Speed: 1600 rpm

Exhaust Pipe Diameter: 3 in

Engine Load	Smoke Opacity, %					
	[illegible]	A. R.	PHS	Bacharach	PHS	Nebetco
0	1.1	0.5	1.7	0.9	1.3	0.3
1/3	7.8	5.6	7.4	5.8	7.6	2.9
2/3	16.0	11.8	15.2	12.8	15.0	6.0
Full	20.0	16.1	19.3	16.0	17.7	8.1

Exhaust Pipe Diameter: 4 in

Engine Load	Smoke Opacity, %					
	PHS	A. R.	PHS	Bacharach	PHS	Nebetco
0	1.1	1.3	1.9	3.0	1.4	0.7
1/3	9.5	10.5	10.4	11.0	11.2	4.6
2/3	22.5	21.8	22.0	21.4	21.9	9.9
Full	27.5	25.6	26.5	27.0	27.5	12.1

Exhaust Pipe Diameter: 5 in

Engine Load	Smoke Opacity, %					
	PHS	A. R.	PHS	Bacharach	PHS	Nebetco
0	1.5	1.3	1.1	2.5	2.3	1.8
1/3	9.8	9.8	11.1	11.0	11.5	3.9
2/3	18.5	18.8	21.3	20.5	23.2	11.3
Full	28.1	28.7	28.7	27.8	28.2	21.0

TABLE 13. STEADY-STATE SMOKE TEST DATA -- SMOKEMETER EVALUATION (Cont'd)

Engine Speed: 2100 rpm

Exhaust Pipe Diameter: 3 in

Engine Load	Smoke Opacity, %					
	PHS	A. R.	PHS	Bacharach	PHS	Nebetco
0	2.6	1.0	1.8	1.1	2.4	0
1/3	10.8	7.5	7.5	6.5	11.2	4.8
2/3	16.5	16.8	13.3	11.0	16.1	6.9
Full	24.8	18.3	21.7	17.0	23.5	9.8

Exhaust Pipe Diameter: 4 in

Engine Load	Smoke Opacity, %					
	PHS	A. R.	PHS	Bacharach	PHS	Nebetco
0	1.7	1.3	1.6	2.1	1.3	0.4
1/3	13.7	11.2	15.0	14.3	14.2	4.1
2/3	20.5	17.0	23.2	20.8	22.2	9.4
Full	30.3	25.8	31.5	28.8	32.5	12.8

Exhaust Pipe Diameter: 5 in

Engine Load	Smoke Opacity, %					
	PHS	A. R.	PHS	Bacharach	PHS	Nebetco
0	4.0	2.1	3.7	4.4	1.6	0.3
1/3	14.3	16.0	15.9	15.5	11.7	4.2
2/3	21.5	21.5	22.0	24.5	19.8	7.0
Full	32.8	31.3	33.0	36.5	32.7	12.6

opacities very close to those of the PHS instrument at zero and one-third engine loads, and then read 2.5- to 3.5- percent opacity higher than PHS at the high smoke levels. The mode of operation of the Nebetco smokemeter was unchanged from previous tests.

Several conclusions can be drawn from the test results for steady-state smoke conditions. First, the Atlantic Research and Bacharach smokemeters agreed much more closely with the PHS instrument, for all of the above engine conditions and pipe sizes, than the Nebetco smokemeter. Second, the differences (in percent opacity) between the readings of the PHS smokemeter and the commercial smokemeters are greater at 2100 engine rpm than at 1600 rpm. Third, the data taken by the commercial smokemeters under steady-state smoke conditions with four-in diameter pipe show the same general trends (when compared to the PHS readings) as the Federal smoke test data discussed in Section I. Last, the differences between the PHS and the other smokemeters decrease as pipe diameter increases, and this condition holds true for the two engine speeds and four loads used in these tests.

It was mentioned previously that the Bacharach smokemeter uses a grid network in the sensor head. The stated purpose of this "eggcrate" is to straighten the exhaust plume before it passes through the smokemeter light beam, and to create a pressure drop that is supposed to sweep air over the optical lenses. The grid assembly is constructed from some lightweight, non-magnetic material, probably aluminum or magnesium. Both of these metals melt at 650-660°C (1200-1220°F). The grid assembly was inadvertently subjected to full-power exhaust temperature from the NH-220 engine for an extended period of time (approximately 3-4 min). The result of this action is shown in Figure 36. The grid material melted and was blown away by the exhaust, leaving a circular hole some 2.5-in. in diameter. While it must be admitted that the Bacharach instrument was not designed for extended use at high exhaust temperatures, this incident does point out the need for caution in its use. No problems were encountered when using this smokemeter during the full-power lugdown of the Federal smoke test. This lugdown is of 30-40 second duration.

Another grid assembly was obtained from Bacharach and installed according to their instructions. This approach, which was approved by the Project Officer, allowed continued use of the same basic instrument. The Bacharach Company offered another instrument as a replacement, but it was feared that use of another smokemeter would disrupt the continuity of the evaluation.

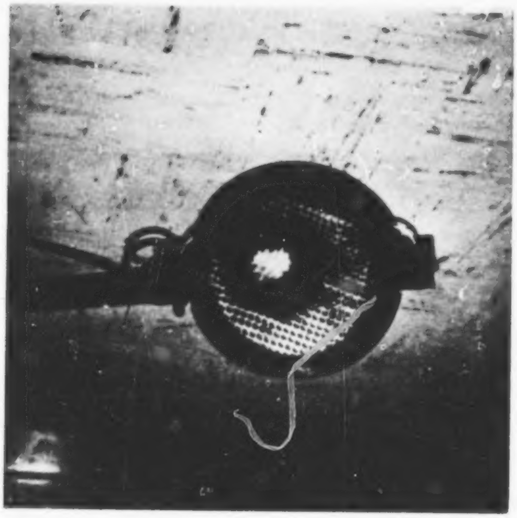


FIGURE 36. DAMAGED GRID IN BACHARACH SMOKEMETER

At this point in the project, a decision was also made by the Project Officer concerning the Nebetco smokemeter. This instrument had consistently failed to demonstrate an acceptable level of performance in the bench tests or the smoke tests. The decision was therefore made to exclude the instrument from further tests, and hence restrict evaluation to the Atlantic Research and Bacharach smokemeters.

2. Truck Smoke Tests

The test plan consisted of performing the complete series of tests (Federal, New Jersey lugdown, SwRI, and New Jersey free acceleration) with the PHS smokemeter, followed by the two commercial instruments and winding up with the PHS. All tests involving a particular vehicle were conducted on the same day. The data shown in Table 14 for the Atlantic Research and Bacharach smokemeters are averages of at least three repeatable runs for each test procedure. The PHS data are averages of at least six repeatable runs.

The data in Table 14 were compared to establish correlations between the PHS smokemeter and the two commercial instruments. This comparison was first done in a qualitative manner, then in a more quantitative way. The data are illusteated in Figures 37 to 44 as an aid to comparison. There are two figures for each of the four engines used in the study. One figure illustrates the time-averaged-data ("a" and "b" factors) and the other shows the peak data for the various accelerations and lugdowns.

TABLE 14. SMOKE TEST DATA FOR PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS FOR FOUR TRUCK TEST PROCEDURES

	Federal (Chassis Dyna.)				New Jersey Truck Lugdown				SwRI Accel. - Max Power				New Jersey Free Accel.
	Smoke Opacity, %				Smoke Opacity, %				Smoke Opacity, %				Smoke Opacity, %
Smokemeter	"a" Factor*	Accel. Peak	"b" Factor*	Lug Peak	"a" Factor*	Accel. Peak	"b" Factor*	Lug Peak	"a" Factor*	Accel. Peak	"b" Factor*	Max. Power Peak	Accel. Peak
	Engine: Cummins NHC-250 (No. 1)												
PHS	13.5	24.2	12.2	16.1	9.6	20.8	8.8	10.8	14.2	18.4	14.5	16.3	15.9
Atlantic Res.	12.5	25.5	12.4	15.7	9.1	17.2	7.6	9.2	16.6	20.0	16.0	17.5	13.2
Bacharach	11.1	20.9	10.2	13.6	10.3	18.3	8.7	10.8	11.5	15.5	11.3	12.5	11.0
	Engine: Cummins NHC-250 (No. 2)												
PHS	35.1	38.8	38.0	40.4	18.0	29.1	31.4	32.4	20.6	29.8	27.0	27.9	29.6
Atlantic Res.	25.6	30.0	27.0	28.4	18.5	26.1	23.1	23.5	24.5	26.2	24.5	24.9	33.8
Bacharach	25.7	33.1	30.4	33.6	18.8	28.4	29.0	31.1	23.9	25.1	22.7	24.5	30.9
	Engine: Cummins NTC-335												
PHS	10.2	38.8	2.6	3.0	42.2	64.0	2.2	2.8	37.6	50.6	2.4	3.0	59.6
Atlantic Res.	8.7	35.9	1.5	2.1	38.8	60.9	1.4	2.2	37.0	52.1	2.0	2.8	58.2
Bacharach	10.7	42.8	3.2	3.6	45.6	77.0	5.1	6.2	45.0	60.4	9.3	10.2	57.2
	Engine: Caterpillar 1150												
PHS	27.2	97.1	24.9	27.4	22.0	79.4	12.6	17.9	26.8	89.3	15.4	18.2	23.2
Atlantic Res.	23.1	93.0	20.0	21.6	24.7	81.4	9.4	10.6	25.0	85.7	12.1	17.0	16.0
Bacharach	28.5	96.5	24.6	26.9	28.1	89.2	13.6	15.2	31.9	88.4	17.8	21.5	21.0

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* Time-averaged data

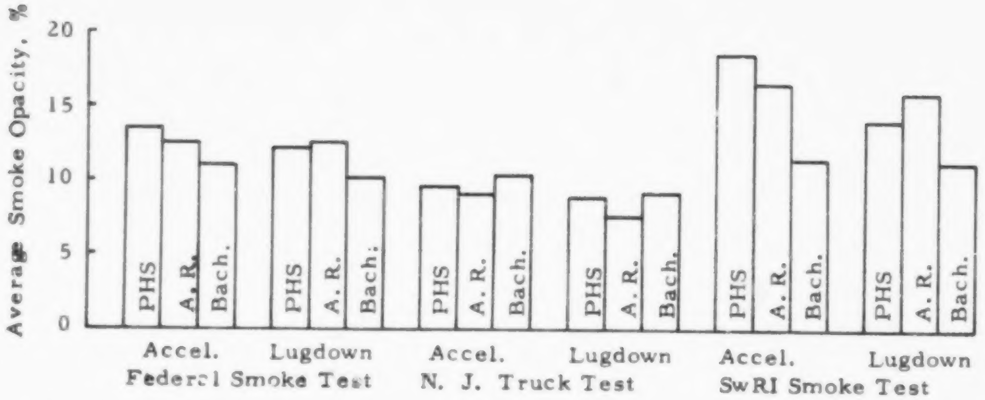

FIGURE 37. TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES - CUMMINS NHC-250 ENGINE (NO. 1)

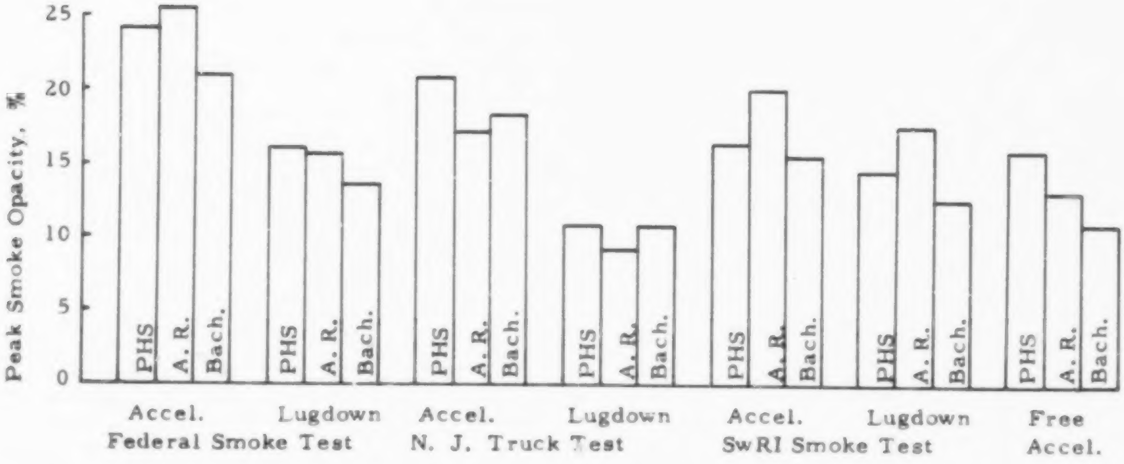

FIGURE 38. PEAK SMOKE TEST OPACITY AS MEASURED BY THE PHS ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES - CUMMINS NHC-250 ENGINE (NO. 1)

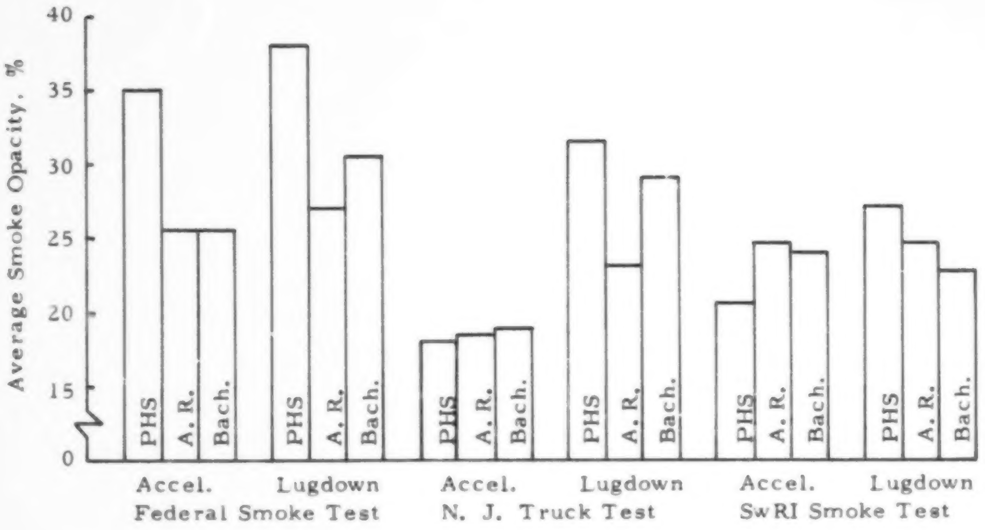

FIGURE 39. TIME AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES - CUMMINS NHC-250 ENGINE (NO. 2)

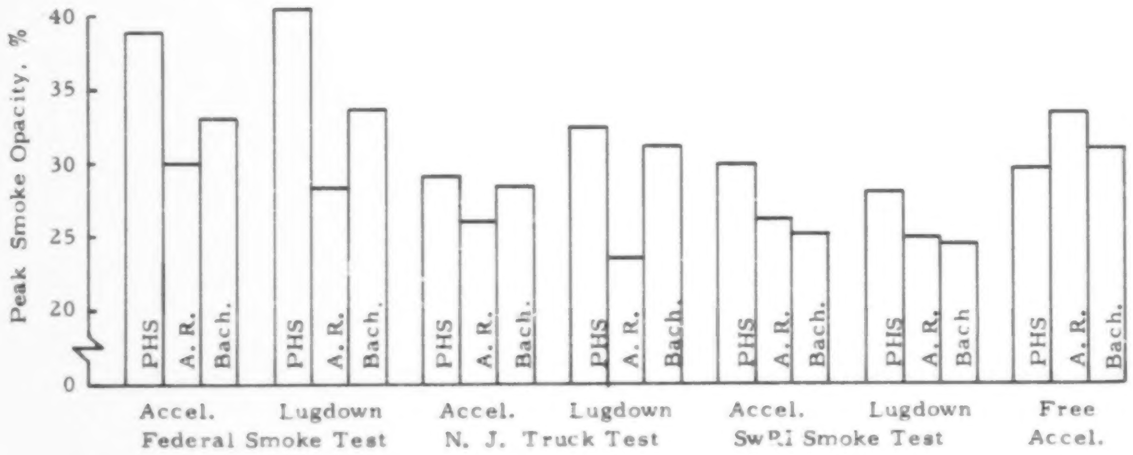

FIGURE 40. PEAK SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES - CUMMINS NHC-250 ENGINE (NO. 2)

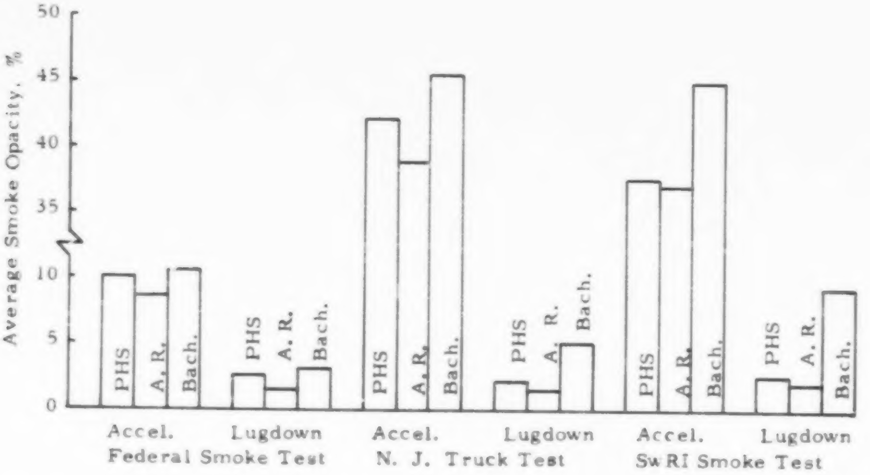

FIGURE 41. TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES - CUMMINS NTC-335 ENGINE

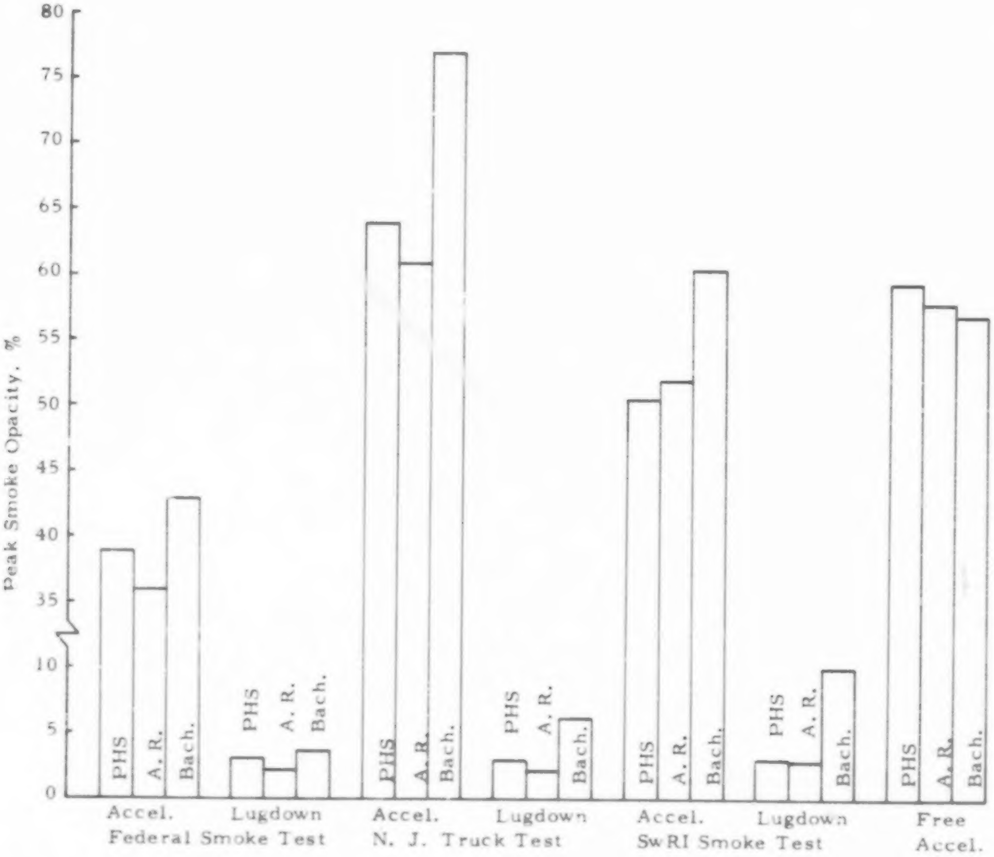

FIGURE 42. PEAK SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES - CUMMINS NTC-335 ENGINE

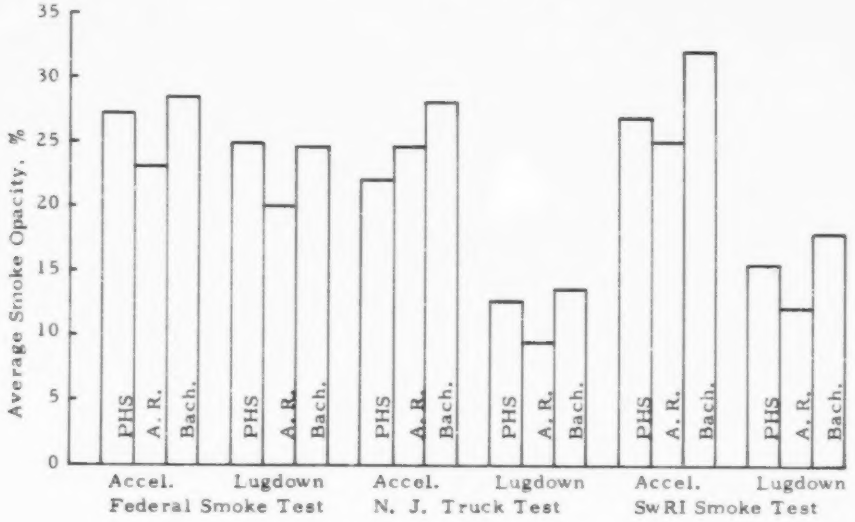

FIGURE 43. TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES - CATERPILLAR 1150 ENGINE

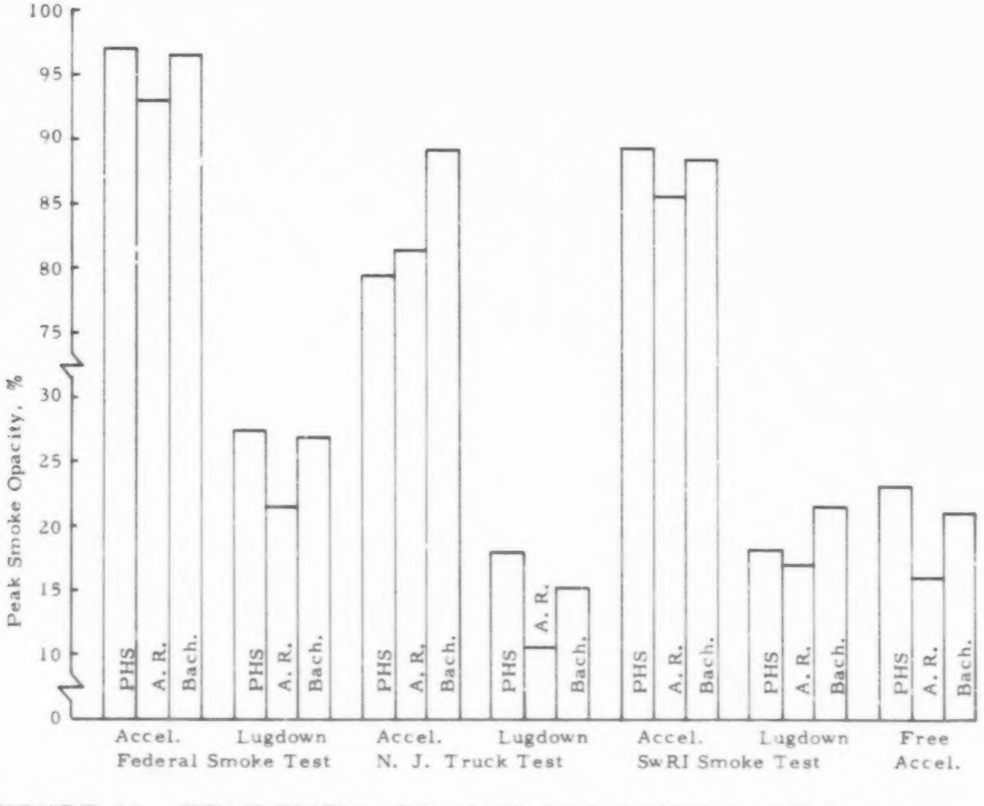

FIGURE 44. PEAK SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES - CATERPILLAR 1150 ENGINE

In comparing the "a" factors generated by the PHS smokemeter with those of the other instruments, it was found that the Atlantic Research correlated best with the PHS in a majority of the tests. The Atlantic Research tended to produce lower "a" factors than the PHS, while the Bacharach "a" factors were generally higher. The Bacharach "b" factors were closest to, and tended to be lower than, the PHS "b" factors. The Atlantic Research also usually read lower lugdown smoke opacity than the PHS smokemeter.

The Atlantic Research instrument correlated best with the PHS in the area of peak acceleration opacity. Both commercial smokemeters generally read lower peak opacity than the PHS. The Bacharach and Atlantic Research correlated best with the PHS in an equal number of instances. Again, both instruments tended to read lower than the PHS. The same qualitative comparison holds true for the free acceleration peak opacities as for the lugdown peak opacities.

An overall summary of the data reveals that the Atlantic Research smokemeter correlated best with the PHS in 52% of the tests, and the Bacharach correlated best in, of course, the remaining 48% of the tests. The Atlantic Research read lower opacity than the PHS 77% of the time (and higher 23% of the time), while the Bacharach read lower 55% of the time (and higher 45% of the time).

The quantitative analysis of the data in Table 14 is summarized below. The numbers given are the average differences, in percent opacity, between the PHS data and the data for the Atlantic Research and Bacharach smokemeters. Note that these differences are derived from readings both above and below the PHS data. This fact is emphasized by the column labled "Bias", which indicates whether the opacity readings tended to be above ("High") or below ("Low") those of the PHS.

	Atlantic Research		Bacharach	
	% Opacity	Bias	% Opacity	Bias
"a" Factors	2.7	Low	3.6	High
"b" Factors	3.2	Low	2.8	Low
Accel. Peaks	3.3	Low	3.8	Low
Lugdown Peaks	3.6	Low	3.0	Low
Free Accel. Peaks	3.9	Low	2.7	Low

This summary of opacity differences shows that the Atlantic Research readings were closest to the PHS readings for the "a" factors and the acceleration peak opacities, while the Bacharach was closest for the "b" factors, the lugdown peaks, and the free acceleration peaks. These quantitative statements differ from those in the qualitative discussion given previously, in that the latter dealt only with the number of instances where one smokemeter read closer to the PHS than did the other smokemeter, while the former deals with specific average magnitudes (percent opacity) of difference. This is pointed out to prevent the reader from thinking there is a contradiction in the fact that both smokemeters read closest to the PHS in an equal number of instances (for, say, the free acceleration tests), yet the readings of one instrument (in this case, the Bacharach) were on the average closer to those of the PHS.

In conclusion, there was little difference between the two commercial smokemeters in this series of comparison tests. The Atlantic Research read closer to the PHS in a slightly greater number of tests, while the Bacharach actually read closer on the average.

3. Bus Smoke Tests

The test plan for this series of tests was to perform the Federal, SwRI, and free acceleration tests on the chassis dynamometer, then perform the New Jersey acceleration test on the road. The nominal smoke opacity of the bus was set at the desired level, and all three chassis dynamometer tests were performed using a given smokemeter to measure opacity. The tests were then repeated, at the same smoke level, with a different smokemeter. The PHS instrument was used initially, followed by the Atlantic Research and Bacharach smokemeters and finishing with the PHS. The data from the commercial smokemeters are the average of three repeatable runs, while the PHS data are the average of six repeatable tests.

The data in Table 15 were compared in the same manner as the data from the truck smoke tests. That is, the comparison was done first in a qualitative manner, then in a more quantitative sense. The data are illustrated in Figures 45 through 52 to facilitate the comparisons. There is one figure for the time-averaged data ("a" and "b" factors) and one figure for each peak opacity data, for each smoke level.

The Bacharach smokemeter read closest to the PHS instrument in a large majority of both average and peak data for all four test procedures. Both commercial instruments read lower than the PHS in nearly every instance. These results agree, on the whole, with the truck test results obtained with these instruments. In those tests the Bacharach produced generally higher "a" factors than the PHS, but read lower than the PHS in the areas of peak acceleration,

TABLE 15. SMOKE TEST DATA FOR PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS FOR FOUR BUS TEST PROCEDURES

	Federal (Chassis Dyna.)				New Jersey Bus. Accel.		SwRI Accel. -Max Power				New Jersey Free Accel.
	Smoke Opacity, %				Smoke Opacity, %		Smoke Opacity, %				Smoke Opacity, %
Smokemeter	"a" Factor*	Accel. Peak	"b" Factor*	Lug Peak	"a" Factor*	Accel. Peak	"a" Factor*	Accel. Peak	"b" Factor*	Max. Power Peak	Accel. Peak
	First Smoke Level										
PHS	5.2	7.2	5.6	6.0	3.5	4.4	4.1	4.4	4.4	4.9	4.6
Atlantic Res.	4.3	5.4	4.3	4.7	2.8	3.5	3.2	3.8	3.1	3.4	3.2
Bacharach	4.2	4.8	4.7	5.1	2.9	3.8	3.5	4.4	4.5	5.1	4.9
	Second Smoke Level										
PHS	13.2	15.6	12.8	14.2	8.0	10.4	10.3	14.0	13.6	14.6	17.0
Atlantic Res.	11.7	13.7	11.1	10.9	6.0	7.6	8.4	10.8	10.3	11.0	13.0
Bacharach	10.8	13.6	9.6	10.4	5.9	8.2	10.0	12.5	11.8	12.3	14.8
	Third Smoke Level										
PHS	21.9	25.0	21.7	22.8	14.2	18.2	19.5	24.2	24.2	25.6	34.5
Atlantic Res.	16.7	19.0	16.9	17.9	11.0	14.1	14.2	18.3	18.5	19.7	29.0
Bacharach	19.5	22.3	18.3	19.0	12.2	15.2	17.4	22.1	22.3	23.0	32.0
	Fourth Smoke Level										
PHS	37.6	43.4	36.4	38.7	20.0	25.1	28.6	34.5	38.9	41.2	47.8
Atlantic Res.	31.1	35.2	30.0	34.1	16.0	20.8	21.6	26.9	31.4	33.2	36.0
Bacharach	34.0	39.9	32.9	34.7	15.9	20.1	23.8	31.1	36.0	37.6	40.0

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*Time Averaged Data

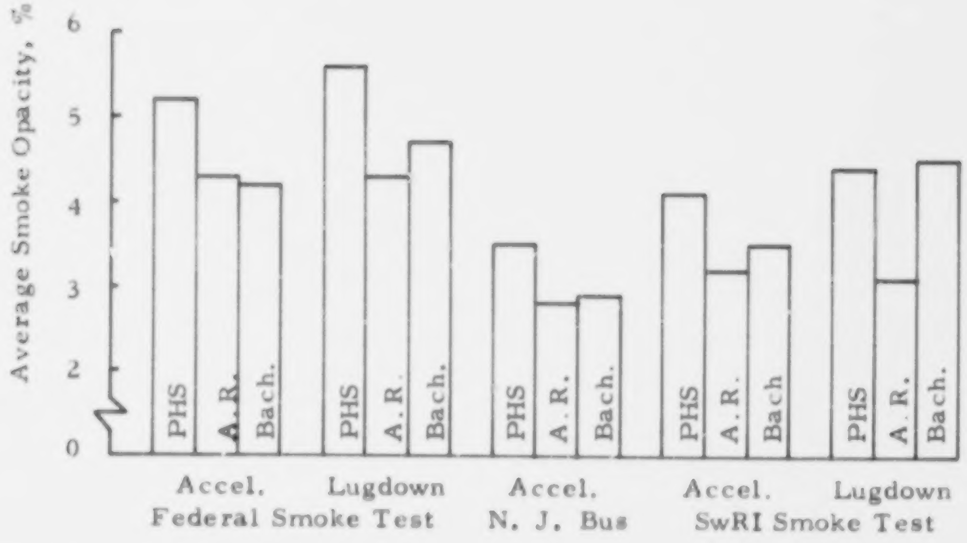


FIGURE 45. TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES -- 6V-71 ENGINE AT FIRST SMOKE LEVEL

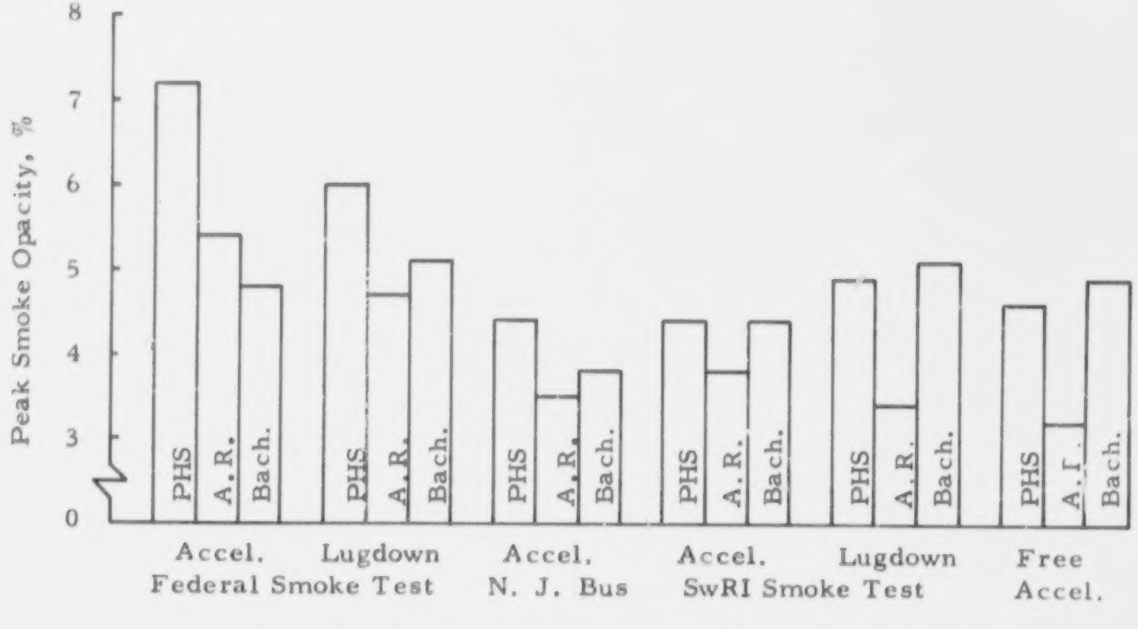


FIGURE 46. PEAK SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES -- 6V-71 ENGINE AT FIRST SMOKE LEVEL

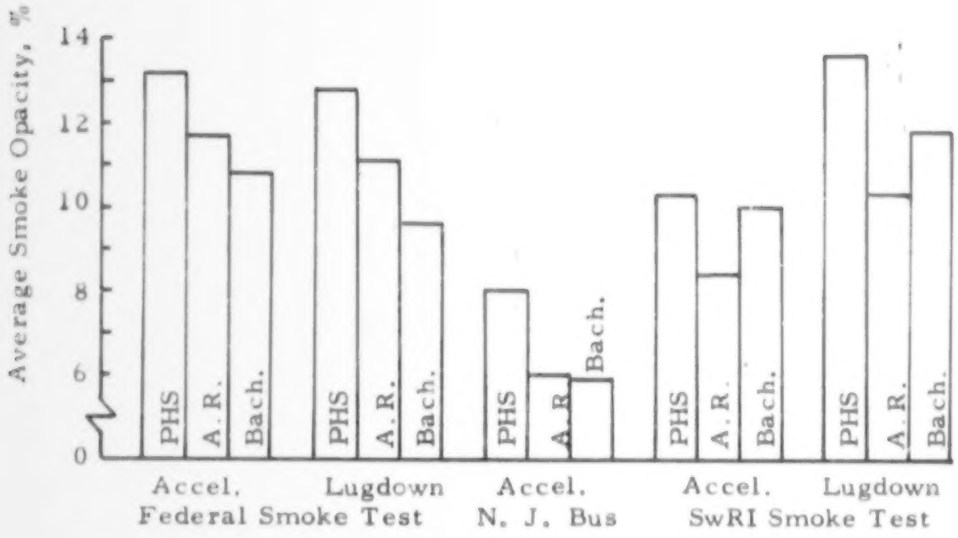


FIGURE 47. TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES -- 6V-71 ENGINE AT SECOND SMOKE LEVEL

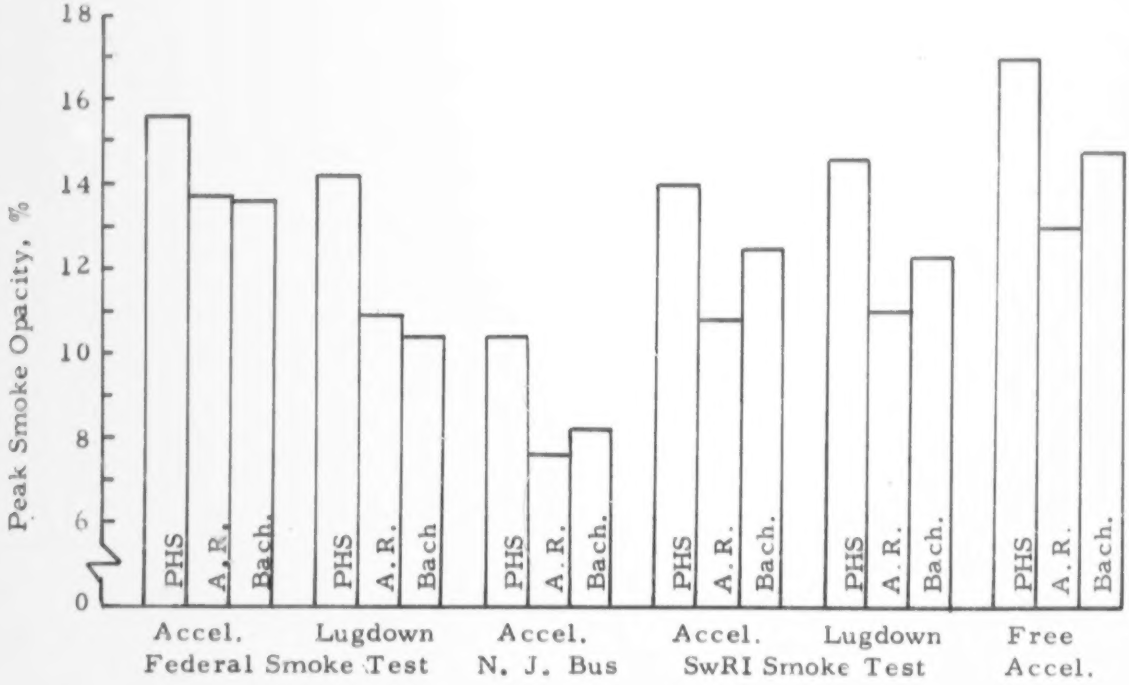


FIGURE 48. PEAK SMOKE OPACITY AS MEASURED BY THE PHS ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES -- 6V-71 ENGINE AT SECOND SMOKE LEVEL

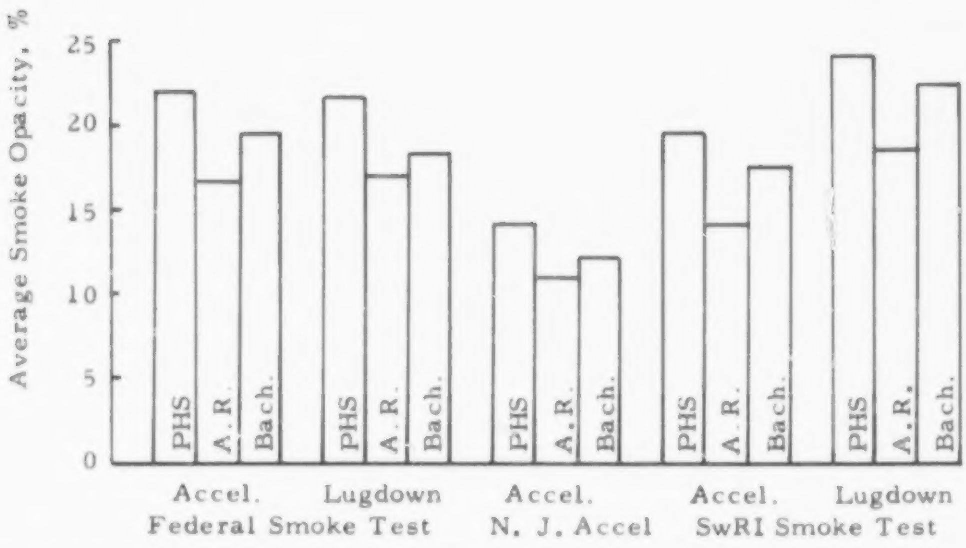


FIGURE 49. TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES -- 6V-71 ENGINE AT THIRD SMOKE LEVEL

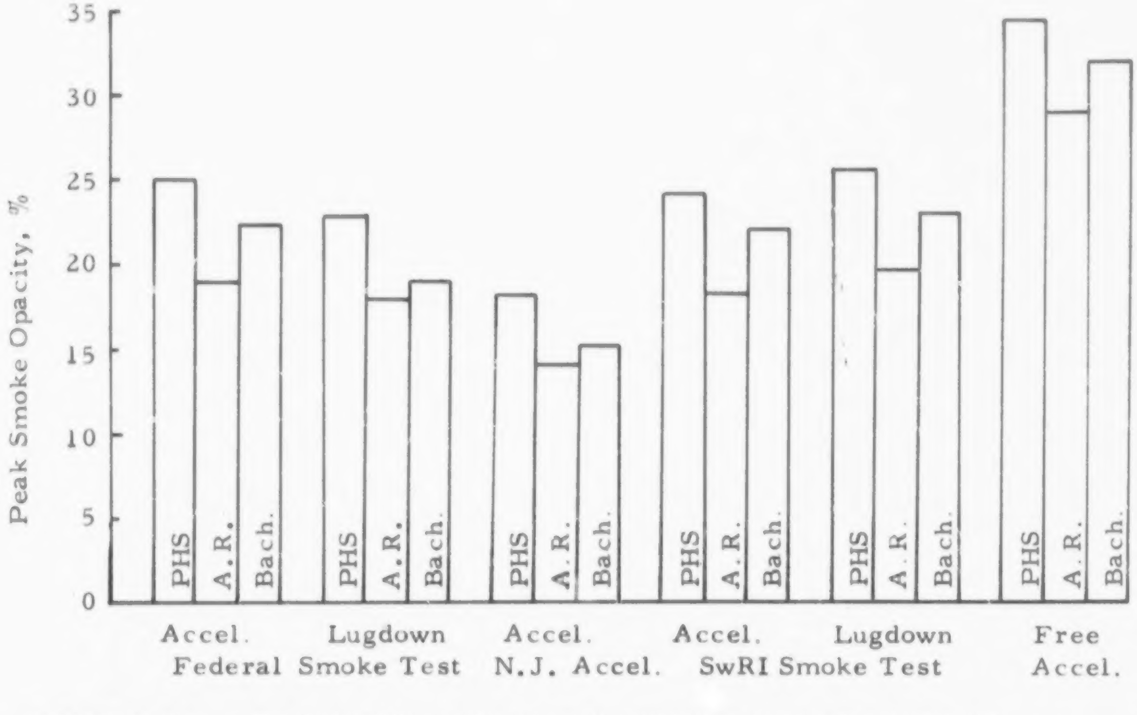


FIGURE 50. PEAK SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES -- 6V-71 ENGINE AT THIRD SMOKE LEVEL

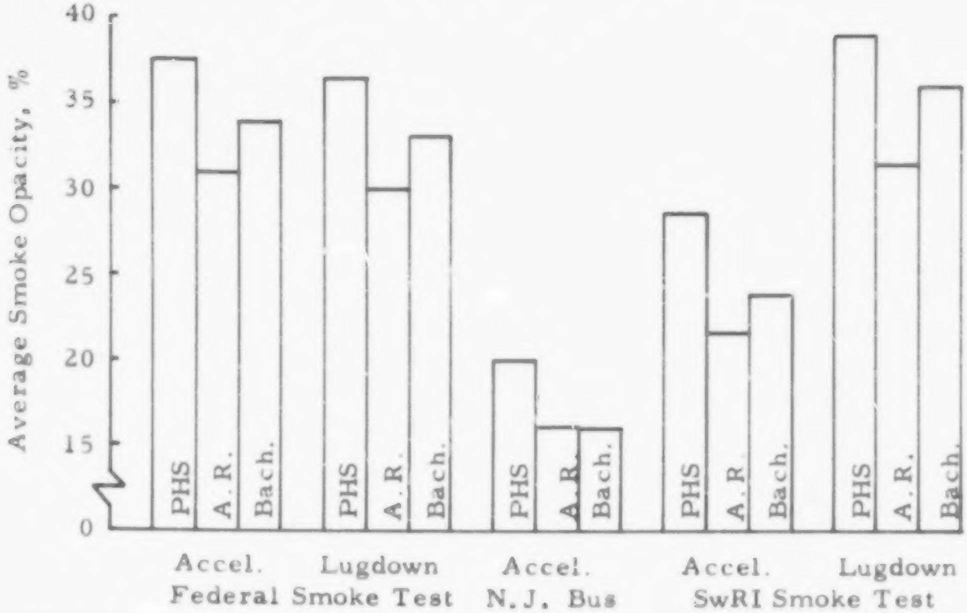


FIGURE 51 TIME-AVERAGED SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR THREE TEST PROCEDURES -- 6V-71 ENGINE AT FOURTH SMOKE LEVEL

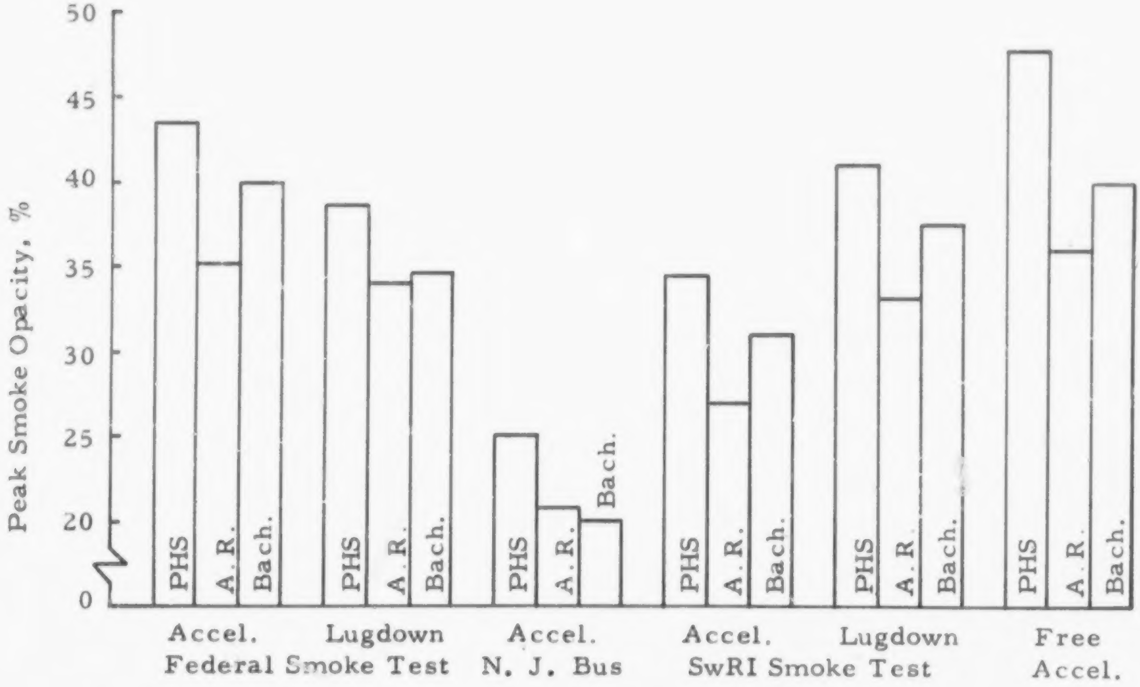


FIGURE 52. PEAK SMOKE OPACITY AS MEASURED BY THE PHS, ATLANTIC RESEARCH, AND BACHARACH SMOKEMETERS, FOR FOUR TEST PROCEDURES -- 6V-71 ENGINE AT FOURTH SMOKE LEVEL

peak lugdown, and time-averaged lugdown opacity. In summary, the Bacharach smokemeter correlated best with the PHS in 79.5% of the tests, while the Atlantic Research correlated best in the remaining 20.5% of the tests. The Atlantic Research read lower than the PHS in every case, and the Bacharach read lower in some 95% of the tests.

The results of the quantitative analysis of the data in Table 15 are given below. The numbers represent the average differences, in percent opacity, between the PHS data and those of the Atlantic Research and Bacharach smokemeters. The column labeled "Bias" indicates whether the opacity readings were generally higher or lower than the PHS readings. Note that the Bacharach smokemeter read much closer to the PHS in every data category than did the Atlantic Research instrument. This is in marked contrast to the trends shown by the data for the truck smoke tests, in which the two commercial smokemeters were approximately equal in their performance, as compared to the PHS instrument.

	Atlantic Research		Bacharach	
	% Opacity	Bias	% Opacity	Bias
"a" Factors	3.3	Low	2.2	Low
"b" Factors	4.0	Low	2.2	Low
Accel. Peaks	3.9	Low	2.4	Low
Lugdown Peaks	4.1	Low	2.6	Low
Free Accel. Peaks	5.7	Low	3.2	Low

IV. OTHER TESTS WITH PHS SMOKEMETERS

The work performed in this section includes two special investigations performed at the request of the Project Officer. The first investigation concerned the degree of correlation that exists between several PHS smokemeters. It was already known that the PHS instruments correlate very well in static filter calibration tests, but little information was available concerning the correlation during actual smoke measurement. Therefore, a series of smoke tests was conducted to determine the consistency of the opacity values obtained with three typical PHS smokemeters.

The second investigation involved a series of smoke tests with a standard PHS smokemeter and two large-diameter PHS smokemeters. These enlarged versions were constructed for use on very large exhaust ducts of non-automotive types of diesel engines. It was deemed of interest to determine the degree of correlation between the large-diameter instruments and the standard PHS smokemeter when they were used on a truck-size engine and exhaust system. The results of this correlation study would also shed light on the effect of the smokemeter light beam path length on opacity readings.

A. Correlation of Three PHS Smokemeters

A series of steady-state smoke tests were performed with the stationary-mounted NH-220 engine, using three PHS smokemeters. These tests were to determine the variation in opacity measurements at various engine speeds and loads for three identical PHS instruments.

The three PHS instruments were mounted on three-, four-, and five- in diameter exhaust pipes on the test stand previously described (Figure 53). The engine speeds used were 1600 and 2100 rpm, and engine loads were zero load, full load, and approximately one-third and two-thirds of full load. After engine load and speed were stabilized, the flexible exhaust pipe was connected in turn to each of the three smokemeters.

The data for this series of tests are contained in Table 16. The excellent agreement shown by the smokemeters is evident. The largest variation was 1.0- percent opacity, and most of variations were 0.5- percent opacity, or less. The smokemeters were calibrated before and after a set of tests for a given pipe size, using neutral density filters of approximately 20- and 36- percent opacity. The calibrations were accurate to ±0.5- percent opacity.

Of special interest is the average smoke opacity for the three PHS smokemeters for each engine speed, load, and exhaust pipe size

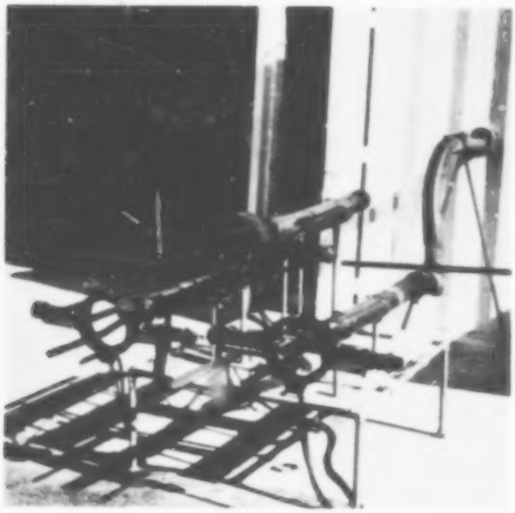


FIGURE 53. THREE PHS SMOKEMETERS ON TEST STAND

(Table 16). Note that the indicated smoke opacity for each engine speed and load increased as the pipe diameter increased. These increases in opacity are shown in Figures 54 and 55 as a function of engine load. The figures illustrate the consistency of the observed changes.

At full engine load at 1600 rpm, the average measured smoke opacity from the three-in pipe was 18.2- percent and that from the five-in pipe was 26.8- percent, an increase of nearly 50 percent. At 2100 rpm and full engine load, the average measured opacity from the three-in stack was 19.7- percent and that from the five-in pipe was 33.7- percent, an increase of over 70 percent.

It should be mentioned here that each smokemeter was mounted on the exhaust pipes such that the distance from the end of the pipe to the center of the light beam was six in. The Federal Register prescribes a distance of 1.0-1.5 pipe diameters when performing the Federal smoke compliance test. Hence, the distance used for this series of tests was within the specified range for four-in and five-in diameter pipes, but was somewhat more for the three-in pipe. However, mounting the smokemeters on the three-in pipes in this manner allowed the rather narrow exhaust plume to diverge and fill the smokemeter ring.

TABLE 16. STEADY-STATE SMOKE TEST DATA FOR THREE PHS SMOKEMETERS

Engine Speed: 1600

Exhaust Pipe Diameter: 3 in

Engine Load	Smoke Opacity, %			
	PHS #1	PHS #2	PHS #3	Average
0	1.0	1.0	1.3	1.1
1/3	6.7	6.2	6.7	6.5
2/3	13.5	13.0	13.0	13.2
Full	18.5	18.0	18.0	18.2

Exhaust Pipe Diameter: 4 in

Engine Load	Smoke Opacity, %			
	PHS #1	PHS #2	PHS #3	Average
0	1.7	1.5	1.5	1.6
1/3	8.5	8.0	8.0	8.2
2/3	16.5	16.5	16.0	16.3
Full	20.0	21.0	20.0	20.3

Exhaust Pipe Diameter: 5 in

Engine Load	Smoke Opacity, %			
	PHS #1	PHS #2	PHS #3	Average
0	2.3	2.0	2.3	2.2
1/3	11.5	11.0	11.0	11.2
2/3	19.5	19.5	18.5	19.2
Full	27.0	26.5	27.0	26.8

TABLE 16. STEADY-STATE SMOKE TEST DATA FOR THREE PHS SMOKEMETERS (con't)

Engine Speed: 2100 rpm

Exhaust Pipe Diameter: 3 in

Engine Load	Smoke Opacity, %			
	PHS #1	PHS #2	PHS #3	Average
0	1.7	1.8	1.6	1.7
1/3	8.7	8.3	8.3	8.4
2/3	12.5	12.0	12.0	12.2
Full	19.5	20.0	19.5	19.7

Exhaust Pipe Diameter: 4 in

Engine Load	Smoke Opacity, %			
	PHS #1	PHS #2	PHS #3	Average
0	2.5	2.5	2.3	2.4
1/3	11.0	11.3	11.5	11.3
2/3	16.5	17.0	17.0	16.8
Full	26.5	26.0	27.0	26.5

Exhaust Pipe Diameter: 5 in

Engine Load	Smoke Opacity, %			
	PHS #1	PHS #2	PHS #3	Average
0	3.5	3.3	3.3	3.4
1/3	14.5	13.5	14.5	14.2
2/3	21.5	22.0	22.0	21.8
Full	33.5	33.5	34.0	33.7

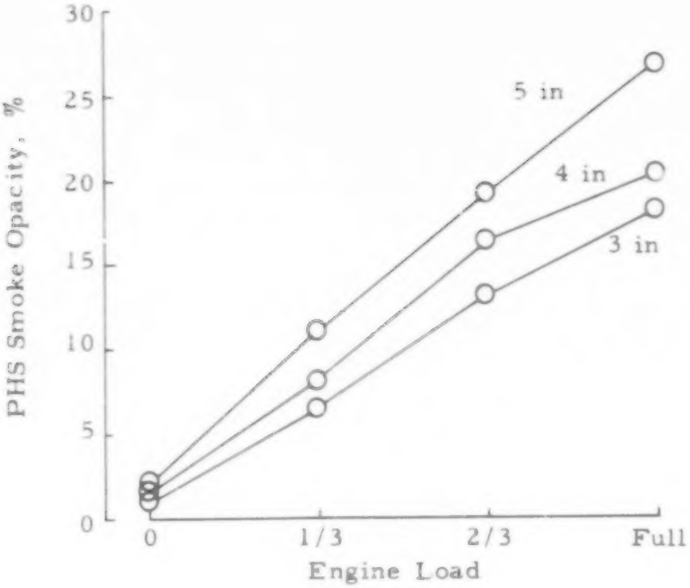


FIGURE 54. EFFECT OF EXHAUST STACK DIAMETER ON SMOKE OPACITY - 1600 RPM

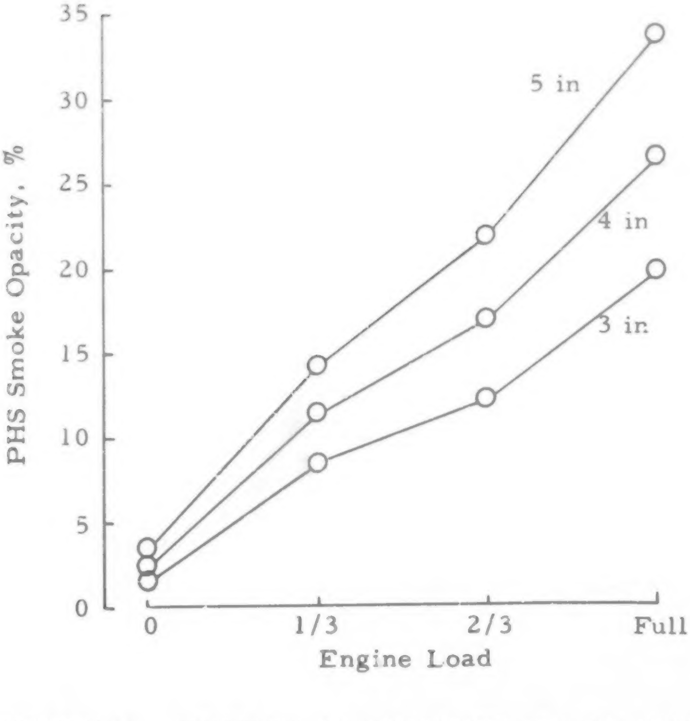


FIGURE 55. EFFECT OF EXHAUST STACK DIAMETER ON SMOKE OPACITY - 2100 RPM

As a matter of interest, the average data in Table 16 for the three-in and five-in diameter pipes were corrected by the Beere-Lambert law. The opacity data for these pipe sizes were calculated on a four-in basis and these corrected data are given in Table 17.

At 1600 rpm, the corrected opacities from the three-in and five-in pipes agree quite well with the measured opacities from the four-in stack. The only anomaly is at full engine load, where the corrected opacities are two- to three- percent opacity higher than the observed opacities for this pipe size. However, note in Figure 54 that the data point for this condition is two- to three- percent opacity low when compared to the other points. (It is likely that the engine was not at full load, and smoke opacity was therefore slightly lower than it should have been.) Hence, the Beere-Lambert law, when applied to the full-load opacity data for the three-in and five-in pipes, predicts the smoke opacity for the four-in pipe. At 2100 rpm, the corrected opacities agree well with the observed opacities for the four-in stack throughout the range of engine loads. The greatest difference is 1.2- to 1.5- percent opacity at approximately 26.5- percent opacity.

It should be noted that the PHS data in Table 13 of the preceding Section also shows an increase in opacity as pipe diameter increases. However, the data in Table 16 was considered more conclusive since they were obtained by three PHS instruments operating in a highly repeatable manner. The data in Table 13 can be considered further substantiation of the effect of pipe size on observed opacity. For further information on this effect, refer to the final report, "An Investigation of Diesel-Powered Vehicle Odor and Smoke - Part II", dated February 1968, 11. 104-7. This report covers work performed under Contract No. PH 86-67-72 for the National Center for Air Pollution Control of the U.S. Department of Health, Education, and Welfare.

B. Correlation of Ten-, Twenty-, and Forty- inch Diameter PHS Smokemeters

Another EPA project performed at the Emissions Research Laboratory (under Contract EHS 70-108, "Study of Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines") called for a series of smoke tests of diesel-powered locomotives. Since the standard PHS smokemeter, with ten-in diameter ring, was much too small for the large exhaust ducts of these engines, two large-diameter PHS instruments of 20- and 40-in diameter were designed and constructed by SwRI. These instruments were constructed using the standard PHS optical components (collimating tubes, lens, lamp, and photocell) and the standard readout box used with the ten-in smokemeter. The 20- and 40-in rings were formed from a band of aluminum four-in wide by one-half in thick.

TABLE 17. SMOKE OPACITY DATA CORRECTED BY BEERE-LAMBERT LAW*

Engine Speed: 1600 rpm

Engine Load	Smoke Opacity, % 3-in Pipe (corrected to 4 in)	5-in Pipe (corrected to 4 in)	4-in Pipe (as measured)
0	1.5	1.8	1.6
1/3	8.5	9.1	8.2
2/3	17.2	15.7	16.3
Full	23.4	22.1	20.3

Engine Speed: 2100 rpm

Engine Load	Smoke Opacity, % 3-in Pipe (corrected to 4 in)	5-in Pipe (corrected to 4 in)	4-in Pipe (as measured)
0	2.2	2.7	2.4
1/3	11.0	11.5	11.3
2/3	15.9	17.8	16.8
Full	25.3	28.0	26.5

---

*The equation of the Beere-Lambert law is

$$O_2 = 100 \left\{ 1.0 - \text{antilog} \left[\log(1.0 - O_1/100) \cdot D_2/D_1 \right] \right\}$$

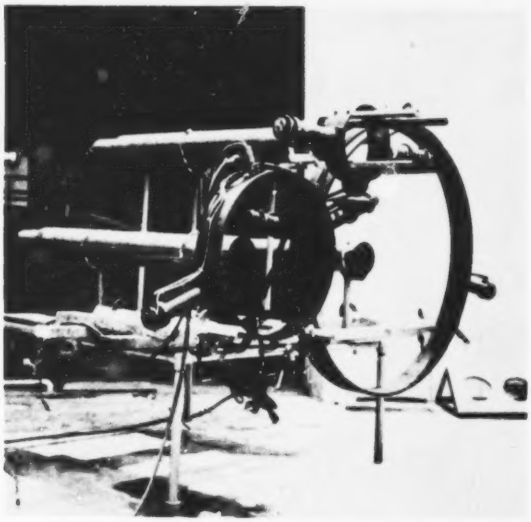
where
O_1 = measured smoke opacity, %
D_1 = actual stack diameter
D_2 = desired stack diameter
O_2 = calculated smoke opacity for stack of diameter D_2

The performance of these instruments was entirely satisfactory. Calibration with neutral density filters was very accurate, and the instruments' response times were judged equal to that of the 10-in diameter smokemeter. The results of the locomotive smoke tests with the large-diameter instruments were likewise termed satisfactory by test personnel.

The Project Officer, when informed of the existence of these smokemeters, requested that a brief series of smoke tests be performed to establish the correlation between their opacity reading and those of the ten-in smokemeter. Accordingly, the 10-, 20-, and 40-in instruments were mounted on the multi-pipe test stand (Figure 56). Three- and four-in diameter exhaust pipes were used, and the Cummins NH-220 engine was operated at 1500 and 2100 rpm. Engine loads were full load and approximately one-third and two-thirds of full load, which resulted in smoke opacities from twelve to forty percent. The test plan consisted of passing exhaust through each of the three smokemeters, in turn, as the engine speed and load were held constant.

The chief result of these tests was the discovery that the nominal opacities registered by the three smokemeters were very close. The emphasis is on "nominal", since there was a substantial difference in the amount of variance, or "hash", in the opacity traces furnished by the three instruments. This phenomenon was more pronounced with the 40-in smokemeter than with the 20-in instrument, and more in evidence with the 20-in than with the standard ten-in smokemeter. It was also more apparent in the tests with four-in diameter pipe than for those with three-in pipe and was greater at 1500 rpm than at 2100 rpm. To site the extremes of the observed variations, the variance from the nominal (or average) opacity measured by the ten-in smokemeter on four-in pipe was approximately ±3.0- percent opacity at 1500 rpm and full load while the 20- and 40-in instruments showed variances of about 5.0- and 8.0- percent opacity, respectively. However, the average opacity values registered by the three smokemeters were within about one percent opacity of each other. When the smokemeters were placed on three-in diameter pipes, the opacity traces obtained at 2100 rpm were virtually identical in their amount of variance and average values.

The speed at which exhaust gases exit the pipe increases when engine speed is increased and/or as the pipe diameter is decreased. Also, the rate at which the smoke diverges from the pipe into a plume is increased as the exit velocity of the exhaust is decreased. Therefore, the amount of "hash" in the opacity traces is related to the exit velocity of the exhaust gases, as well as to the usual influence of exhaust pulsations. This relationship is well known to most users of the PHS smokemeter. The point to be made here is that this effect is magnified when



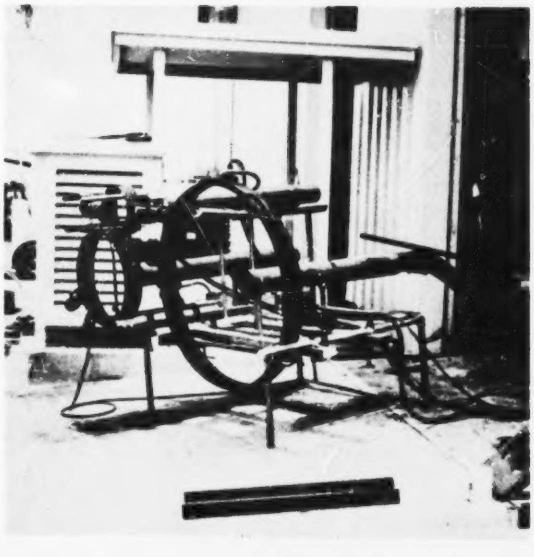


FIGURE 56. TEN-, TWENTY-, AND FORTY-INCH DIAMETER PHS SMOKEMETERS ON TEST STAND

the size of the smokemeter ring is increased. Since the light beam path length is increased in the 20- and 40-in instruments, it is important to note that there was little discernible difference in the nominal opacities measured by the three smokemeters. Hence, the effect of a longer path length on measured opacity appears to be nil, at least for this series of tests with a truck-size diesel engine with highly pulsating exhaust flow.

V. EVALUATION OF OTHER COMMERCIAL SMOKEMETERS

The smokemeters from Atlantic Research, Bacharach, and Nebetco were selected in advance of the beginning of the project as the commercial instruments which would undergo evaluation. Shortly after the project began, the Project Officer expressed interest in three other commercial smokemeters. One was an inline instrument made by Atlantic Research, while the other two smokemeters, one an inline model and the other for end-of-line use, were made by the Robert H. Wager Co.

The evaluation test plan for these instruments took two different forms. First, since the Atlantic Research inline was already in production and in actual use in some research programs, it was decided to subject this instrument to the complete series of bench tests and an extensive series of smoke tests. Second, the Wager instruments were prototypes not yet in production. It was therefore decided that these smokemeters should undergo a somewhat abbreviated series of bench and smoke tests. The results of these tests would determine whether the two smokemeters would be subjected to further evaluation.

A. Evaluation of Atlantic Research Inline Smokemeter

The Atlantic Research Corporation furnished a Model 103 inline smokemeter to the project for evaluation. This instrument was subjected to a series of bench tests and smoke tests similar to those performed with the other smokemeters in the project.

1. Description

The smokemeter sensor unit consists of a six-in OD pipe fitted inside an eight-in OD pipe (Figure 57). Both pipes have one-eighth in wall thickness, and there is approximately seven-eighths in clearance between them. The inner pipe is 15-in long and the outer pipe is 13-in long. A flange is welded to each end of the inner pipe and matching flanges are welded to the exhaust pipes entering and exiting the smokemeter. A split-ring clamp holds the two flanges together. There was no apparent leakage of exhaust from between the flanges.

The optical system of the inline smokemeter is similar, if not identical, to that of the manufacturer's end-of-stack instrument. The light source is a solid-state emitter operating at a frequency of 1000 Hz. The detector is a solid-state photodiode. The optics are contained in two phenolic modules that screw into the two finned collimating tubes. Cleaning the optical lenses is accomplished by removing these optical modules from the collimating tubes (Figure 58). The collimating tubes screw into the outer pipe of the smokemeter and fit securely against the inner pipe, thus forming a closed, leak-proof system (Figure 59).

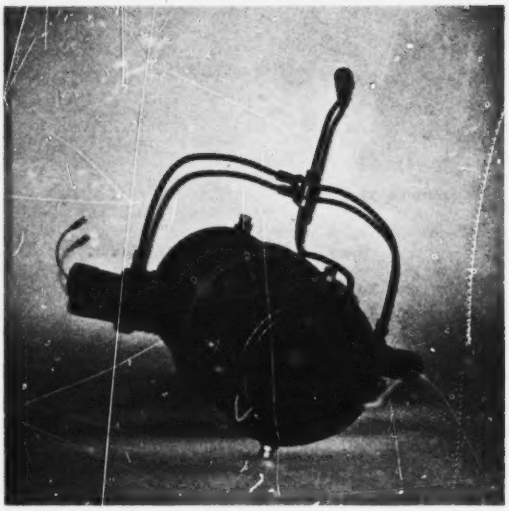


Figure 57. Atlantic Research Inline Smokemeter (End View)

Figure 58. Collimating Tube and Screw-In Optical Module

Figure 59. Screw-In Collimating Tube and Inline Smokemeter (Side View)

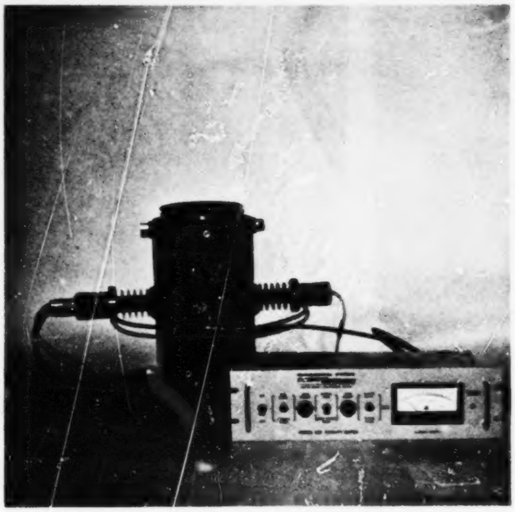


Figure 60. Inline Smokemeter and Control-Readout Box

The smokemeter uses about 2.5 SCFM of compressed air at about 30 psi to purge the collimating tubes of exhaust. Part of this air is diverted into the space between the inner and outer pipes to cool the unit and hence combat thermal distortion of the optical system. The optical lenses were found to be clean even after extended full-load engine operation, and baseline drift was nil.

The control-readout box (Figure 60) contains an on-off switch, "zero" and "full-scale" adjustments, selector switch for either continuous or peak opacity readings, another selector switch for either 0-20 percent opacity or 0-100 percent opacity ranges, and opacity meter. An external output jack provides a nominal 100-millivolt signal for a strip chart recorder. A heavy-duty shielded cable joins the sensor head and the control-readout box.

2. Results of Smokemeter Bench Tests

The data for the bench tests of the Atlantic Research inline smokemeter are presented below. The data for the same series of tests with the PHS end-of-stack instrument are reproduced from Section III to allow direct comparison of the two instruments' performance.

a. Static Filter Calibration Test

The results of the filter calibration of the PHS and AR inline smokemeters are given in Tables 18 and 19, respectively. The accuracy of the PHS instrument is readily apparent from this data. The Atlantic Research smokemeter had more meter error than the PHS, and this error ranged from 0.5- to 5.0- percent opacity high. Figure 61 shows the meter reading and error as functions of filter opacity. Smokemeter output ranged from 103 millivolts at zero opacity to three millivolts at 100-percent opacity. The observed output and linearity error for the AR instrument are shown in Figure 62.

b. Zero Drift

The zero, or baseline, drift was measured over a one-hour period. The data appears below.

Elapsed Time, Minutes	Zero Drift, % of Chart	
	PHS	A. R. Inline
5	0	0
10	+0.2	0
15	+0.2	+0.1
20	+0.2	+0.1
30	+0.2	+0.2
45	+0.3	+0.2
60	+0.3	+0.3
Maximum Drift	+0.3	+0.3

TABLE 18. CALIBRATION DATA FOR PHS SMOKEMETER (END-OF-STACK)

O_F Filter Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	10.0 (=Vc)	10.0	0
100	100*	0	0 (=Vo)	0	0
15.5	15.3	-0.2	8.47	8.45	+0.2
22.5	23.0	+0.5	7.70	7.75	-0.5
37.5	38.3	+0.8	6.17	6.25	-0.8
49.5	50.0	+0.5	5.00	5.05	-0.5
61.0	62.0	+1.0	3.80	3.90	-1.0
73.0	74.0	+1.0	2.60	2.70	-1.0
86.0	86.4	+0.4	1.36	1.40	-0.4
Opaque	100.0	0	0	0	0
Clear	0	0	10.0	10.0	0

*Meter adjusted to these values.

TABLE 19. CALIBRATION DATA FOR ATLANTIC RESEARCH MODEL 103 INLINE SMOKEMETER

O_F Filter Value, % Opacity	O_M Meter Value, % Opacity	E_M Meter Error, % Opacity	V_M Observed Millivolts	V_F Theoretical Millivolts	E_L Linearity Error, %
0	0*	0	103.0 (=Vc)	103.0	0
100	100*	0	3.0 (=Vo)	3.0	0
15.5	-	-	-	-	-
22.5	23.5	+1.0	78.0	80.5	-2.5
37.5	40.0	+2.5	60.0	65.5	-5.5
49.5	50.0	+0.5	54.0	53.5	+0.5
61.0	66.0	+5.0	36.0	42.0	-6.0
73.0	74.0	+1.0	30.0	30.0	0
86.0	89.0	+3.0	15.0	17.0	-2.0
Opaque	100	0	3.0	3.0	0
Clear	0	0	103.0	103.0	0

*Meter adjusted to these values.

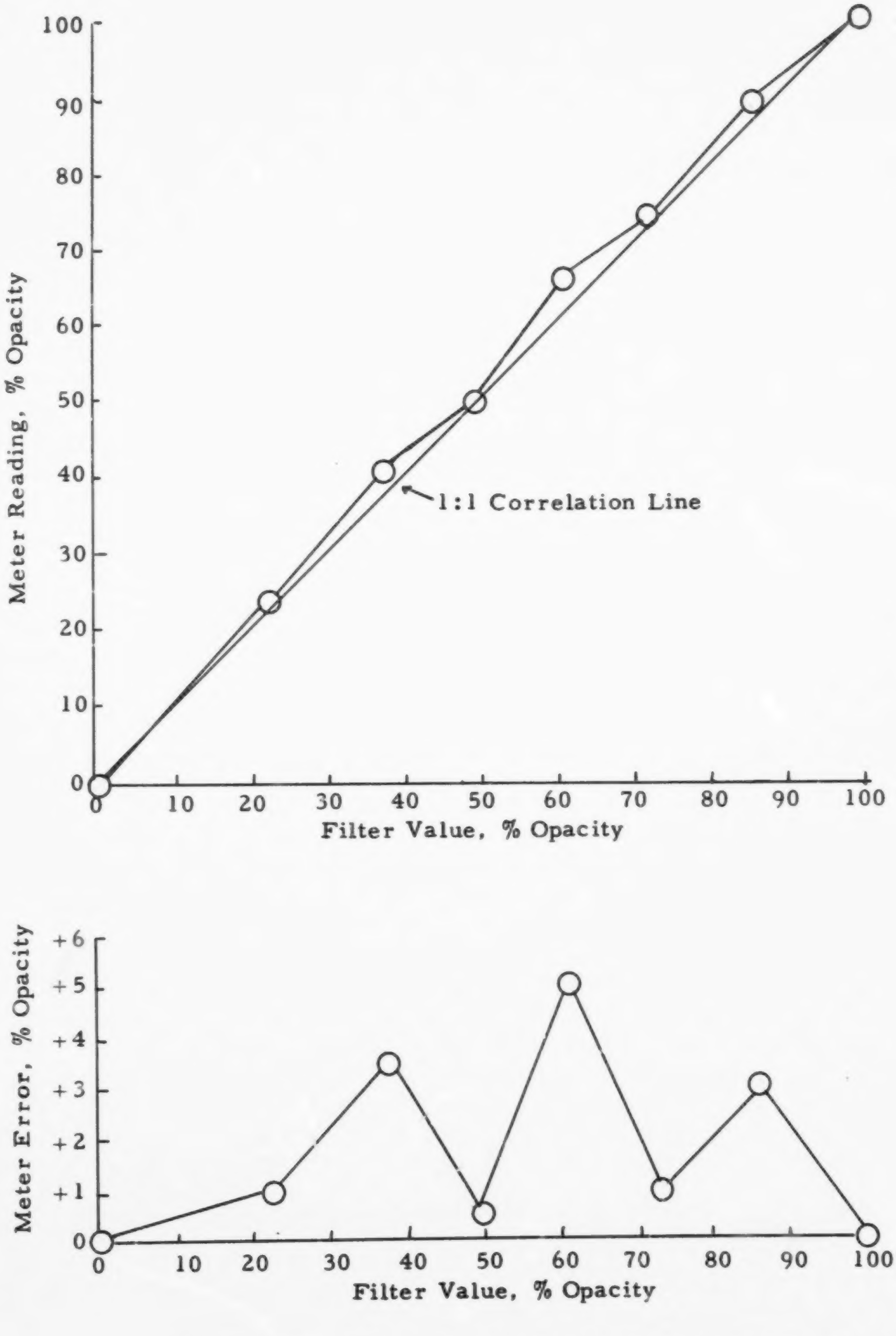


FIGURE 61. METER READING AND ERROR OF ATLANTIC RESEARCH INLINE SMOKEMETER

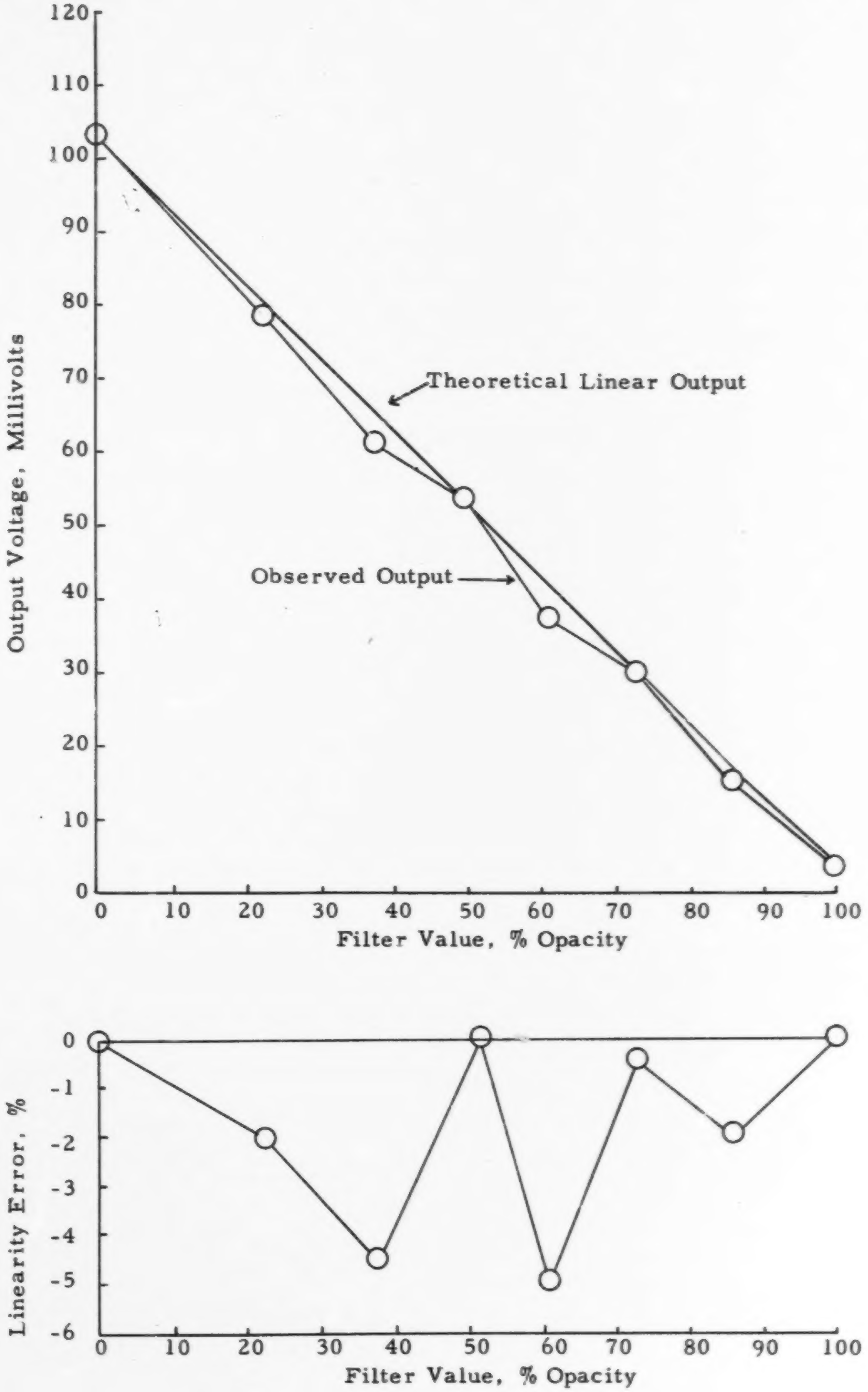


FIGURE 62. OUTPUT VOLTAGE AND LINEARITY ERROR OF ATLANTIC RESEARCH INLINE SMOKEMETER

The two instruments had almost identical baseline changes. At the end of the one-hour period, the full-scale (opaque) settings were checked, and neither instrument showed any change.

c. Effect of Ambient Light

The effect of ambient light on the Atlantic Research inline smokemeter is academic, since no light can enter the instrument when it is installed in an exhaust system. However, an attempt was made to shine the beam of a 125-watt spotlight into the smokemeter's optical system. This activity produced no detectable change in the baseline, half-scale, or full-scale settings of the instrument.

d. Effect of Ambient Temperature

The effect of changes in ambient temperature on the instruments' zero, half-scale (50-percent opacity) and full-scale settings were measured as functions of ambient temperature. The temperatures used in these tests were 75 (baseline), 100, 125, and 150 degrees F. Test results are given in Table 20. The observed changes in zero and half-scale readings of the A. R. smokemeter are graphed in Figure 63.

The A. R. showed almost no change in its zero setting when the ambient temperature was increased from 75°F to 100°F. A slight upward shift (1.4- percent opacity) was noted at 125°F, and a 3.4-percent opacity increase noted at 150°F. These changes were approximately one-half those of the PHS instrument at the same temperatures.

The half-scale (50- percent) changes by the A. R. inline were very slight, the maximum being less than one percent at 150°F. By contrast, the PHS showed a 4.0- percent opacity increase at this temperature. The PHS smokemeter showed no change in its full-scale (opaque) setting as the ambient temperature increased. However, the A. R. had a drop of 3.0- percent opacity at 100°F, and decreases of 1.5- and 2.0- percent opacity at 125 and 150 degrees, respectively.

e. Time Response

The full-scale response time of the A. R. inline smokemeter was measured in the same manner as the other smokemeters; i. e., a sphere was dropped through the light beam and a photograph taken of the resulting time-voltage trace displayed on an oscilloscope. The response times thus obtained are given below, along with the times for the PHS instrument.

Smokemeter	Response Time, sec 0-100%	 100-0%
PHS	0.008	0.008
A. R. Inline	0.007	0.012

TABLE 20. EFFECT OF AMBIENT TEMPERATURE ON SMOKEMETER ZERO, HALF-SCALE, AND FULL-SCALE SETTINGS

Ambient Temp., °F	Zero Change, % Opacity	
	PHS	A. R. Inline
75*	0	0
100	+1.0	+0.3
125	+3.0	+1.4
150	+7.0	+3.4

	Half-Scale Change, % Opacity	
	PHS	A. R. Inline
75*	0	0
100	+0.2	0
125	+1.3	+0.2
150	+4.0	+0.6

	Full-Scale Change, % Opacity	
	PHS	A. R. Inline
75*	0	0
100	0	-3.0
125	0	-1.5
150	0	-2.0

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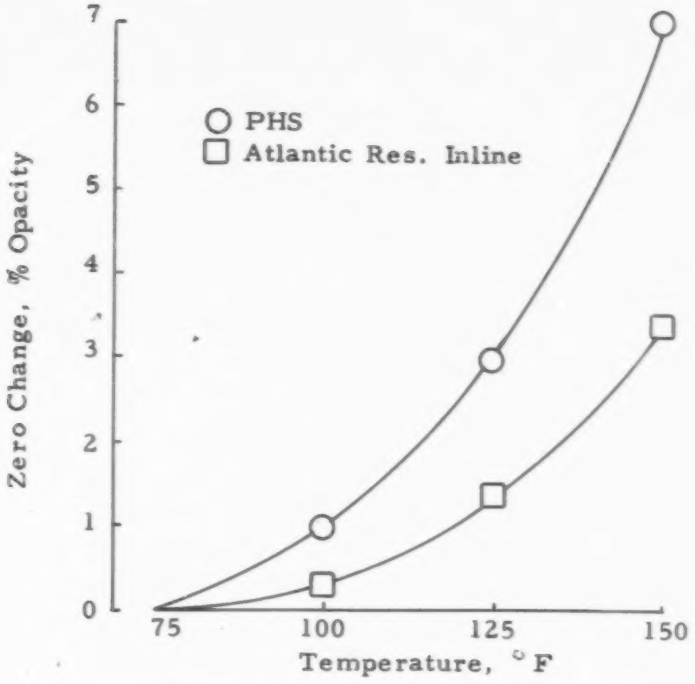
*Baseline temperature.



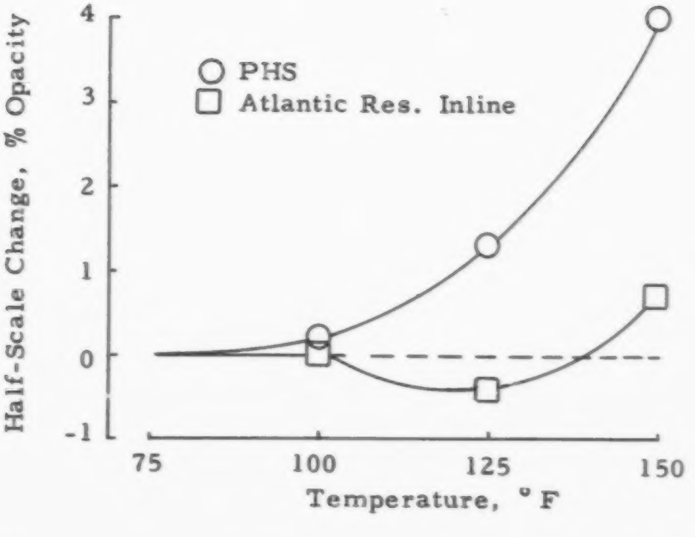


FIGURE 63. CHANGES IN ZERO AND HALF-SCALE READINGS AS A FUNCTION OF AMBIENT TEMPERATURE

Hence, the response times of the A. R. smokemeter are comparable to those of the PHS instrument.

3. Smoke Tests

The A. R. inline and the PHS smokemeter were next mounted on the Cummins NH-220 engine for a series of Federal smoke compliance tests. Three, four, and five-in diameter exhaust pipes were adapted to the inline smokemeter, and the PHS instrument was mounted at the end of the exhaust system (Figure 64).

The Federal "a" and "b" factors measured by the two smokemeters are summarized in Table 21 for each pipe diameter. The smoke factors for the A. R. instrument are given as measured (observed) and after correction by the Beere-Lambert law to the diameter of the exhaust pipes entering and exiting the inline instrument. Figure 65 illustrates these data.

TABLE 21. FEDERAL SMOKE TEST DATA

Smokemeter	"a" Factor	"b" Factor
3-in Pipe		
PHS	20.8	30.8
A.R. Inline (observed)	35.4	44.5
A.R. Inline (corrected)	19.6	25.5
4-in Pipe		
PHS	22.8	33.6
A.R. Inline (observed)	31.0	37.8
A.R. Inline (corrected)	22.0	27.2
5-in Pipe		
PHS	26.6	40.1
A.R. Inline (observed)	27.8	35.6
A.R. Inline (corrected)	23.8	30.7

Note that the PHS and observed A. R. data tend to converge as pipe diameter is increased. The best agreement occurred with the five-in diameter pipe, and the worst agreement was found with three-in pipe. The PHS opacity of the "a" and "b" factors increased with pipe diameter, as was shown in Section IV. The A. R. Inline instrument, on the other hand, registered lower observed opacity with increased pipe size. However, the corrected A. R. opacities increased with pipe diameter.

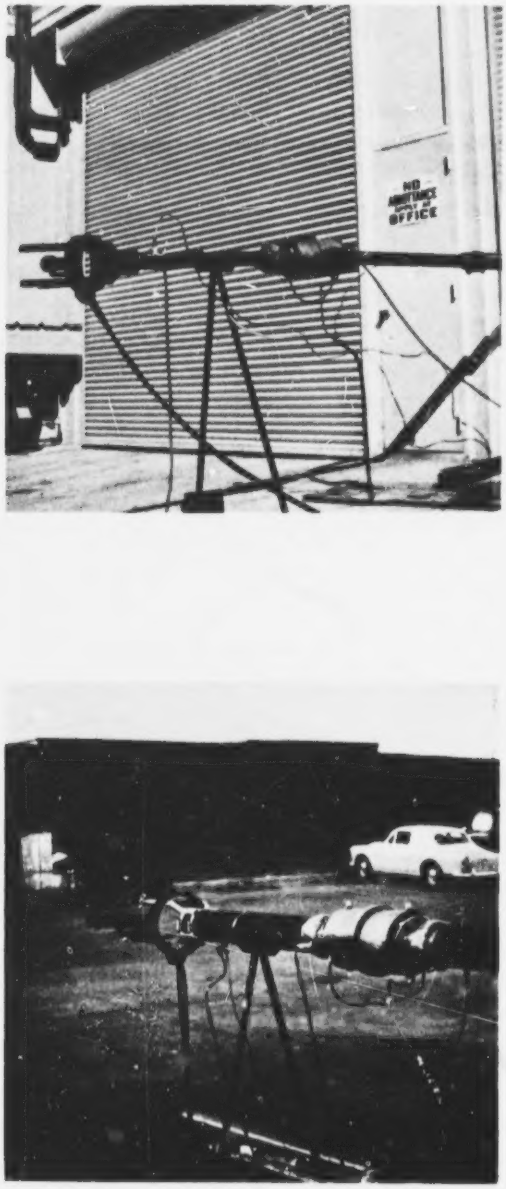

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FIGURE 64. ATLANTIC RESEARCH INLINE SMOKEMETER IN CONJUNCTION WITH PHS SMOKEMETER ON THREE-IN PIPE (TOP) AND FIVE-IN PIPE (BOTTOM)

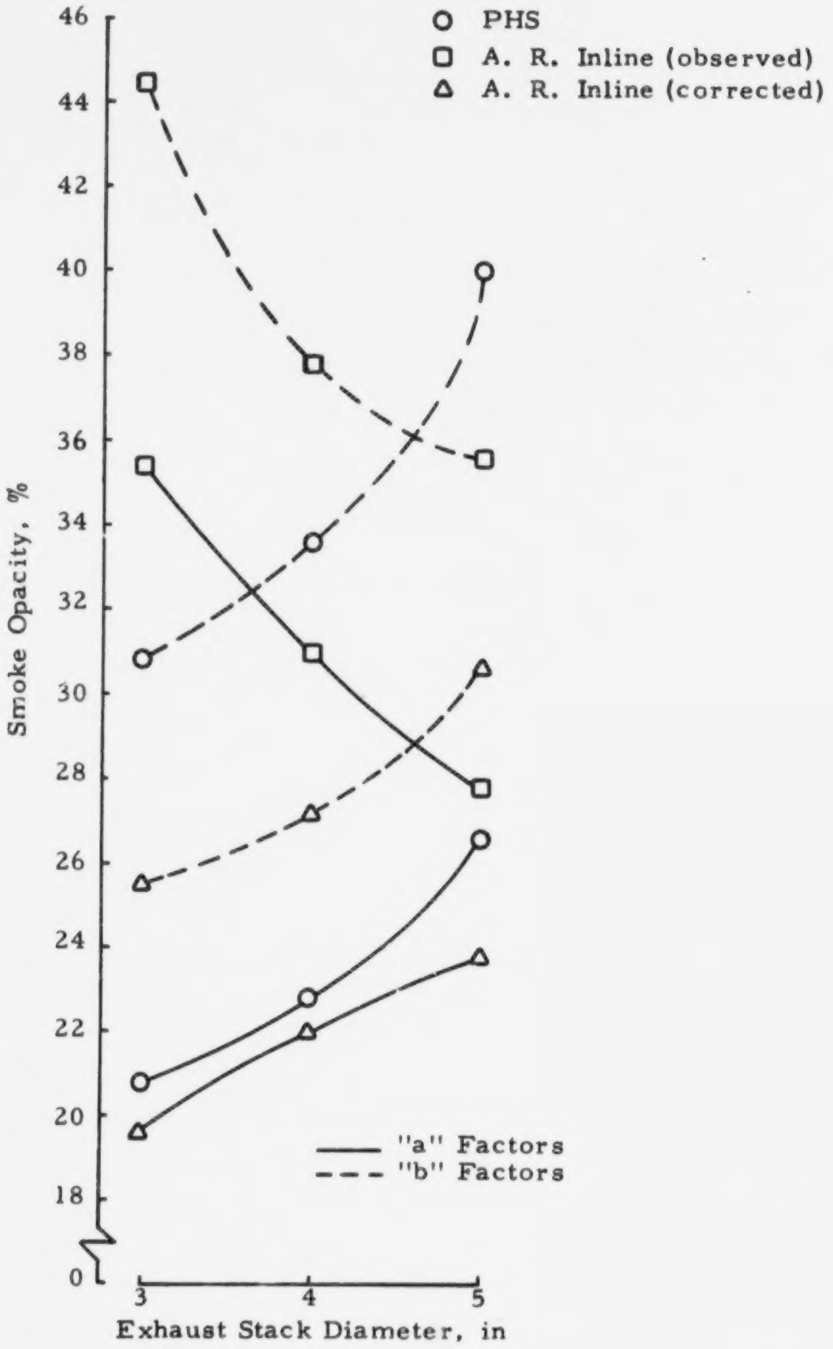

FIGURE 65. PHS AND A. R. INLINE SMOKE OPACITY DATA FOR THREE EXHAUST PIPE DIAMETERS

The corrected inline "a" factors agree quite well with the PHS "a" factors for the three-in and four-in pipes. Less agreement was obtained in the case of the five-in pipe, but here the observed opacities were very close. The observed PHS "b" factors and corrected A. R. "b" factors were closest for three-in pipe and showed the greatest difference for the five-in pipe. However, in no instance did the "b" factors generated by the two smokemeters approach to a reasonable agreement.

B. Evaluation of Wager Smokemeters

Two smokemeters manufactured by the Robert H. Wager Co. were obtained from the manufacturer and subjected to a brief series of evaluation tests. At the time of these tests, these smokemeters were being considered for possible inclusion in the project. Hence, this series of tests was merely to decide whether these instruments should be subjected to further tests and evaluation. A representative of the Wager Company and an EPA representative were present during all tests involving the smokemeters.

One of these smokemeters, shown in Figures 66, 67 and 68, was an end-of-line unit built to meet New Jersey specifications. The other instrument, shown in Figures 69, 70, 71 and 72 was designed for inline opacity measurement and utilized the same optical components (light source, focusing lens, and photocell) as the PHS instrument. This inline unit used purge air to keep the optical system clean, and a flow of water to cool the photocell and light source.

Both instruments were tested for accuracy using the neutral density filters previously described. The accuracy of the portable Wager unit was good and that of the inline instrument was excellent. The portable instrument showed a slight sensitivity to ambient light, while the inline unit showed none. There was insufficient time available to perform the tests for zero drift and effect of ambient temperature.

The two smokemeters were next tested on the Cummins NH-220 engine. Under steady-state smoke conditions, the portable smokemeter experienced a build-up of smoke deposit on the optical lens after about 30 to 60 seconds of operation. When the engine was shut down, the instrument continued to read about 4- to 6- percent opacity. The meter reading returned to zero only when the optical surfaces were cleaned; hence, it was concluded that the problem was one of carbon build-up and not of temperature effects. The smokemeter was operated in both continuous reading and peak reading modes. In the continuous reading mode the meter read some 6- to 8- percent opacity lower than the PHS instrument under similar conditions. When the peak

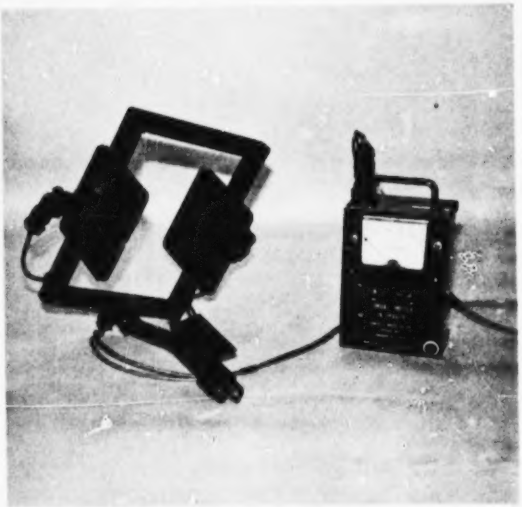

FIGURE 66. WAGER PORTABLE SMOKEMETER AND READOUT UNIT

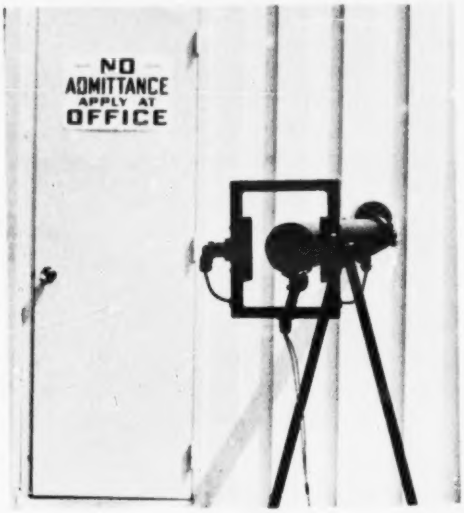
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FIGURE 67. WAGER SMOKEMETER MOUNTED ON EXHAUST STACK

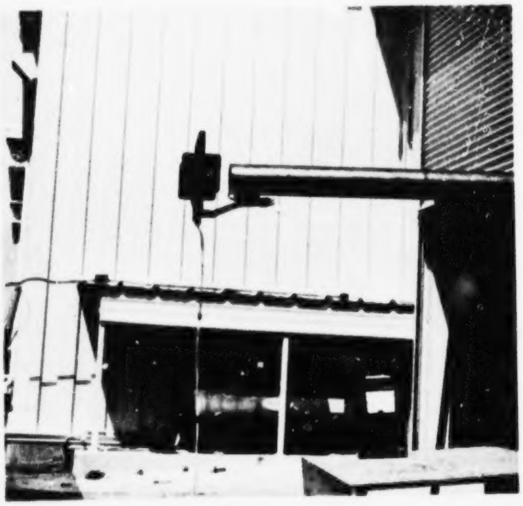

FIGURE 68. WAGER SMOKEMETER MOUNTED ON EXHAUST STACK

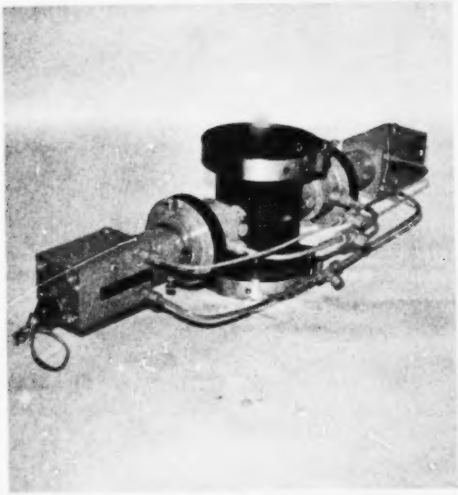

FIGURE 69. WAGER INLINE SMOKEMETER

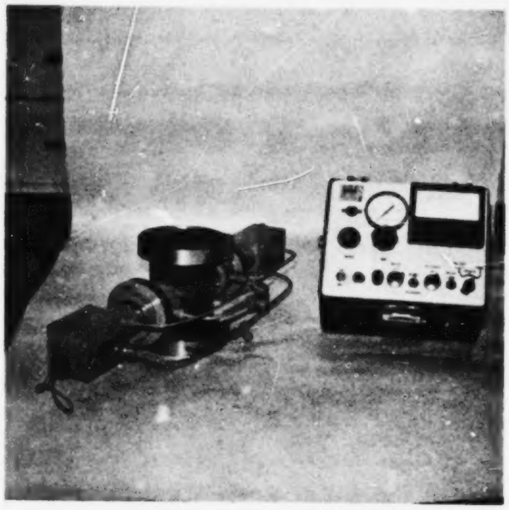

FIGURE 70. WAGER INLINE SMOKEMETER WITH CONTROL BOX

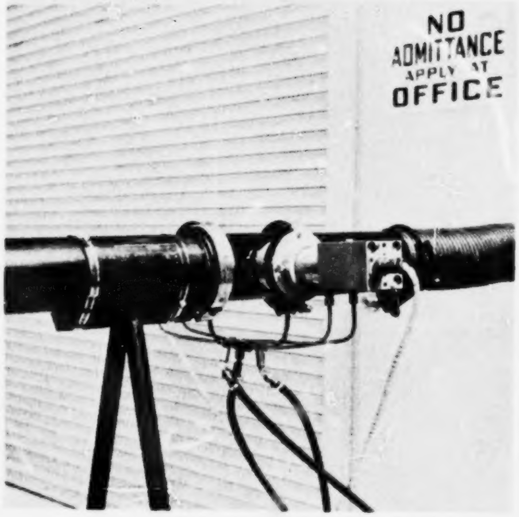
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FIGURE 71. WAGER INLINE SMOKEMETER MOUNTED IN EXHAUST LINE

FIGURE 72. WAGER INLINE SMOKEMETER IN CONJUNCTION WITH PHS SMOKEMETER

reading mode was used, the reading obtained was substantially higher than the continuous reading and similar to the PHS smokemeter reading. The Wager representative concluded that the continuous reading circuitry required some revision to equalize the sensitivity in the continuous and peak reading modes.

The inline Wager instrument was installed in the exhaust line of the Cummins NH-220 and the PHS smokemeter attached to the end of the line (Figure 72). After about one minute of steady-state operation, the inline smokemeter registered 100- percent opacity, and this reading persisted even when the engine was shut down. Examination revealed that the optical surfaces were covered with carbon build-up. It was evident that the purge air system and instrument design were not adequate to keep the optical surfaces clean.

Since both smokemeters experienced problems during these preliminary tests, and since both instruments were in the prototype category, the Wager representative asked that the instruments be returned to the manufacturer. The Project Officer, when advised of the results of these tests, decided that both Wager smokemeters should not undergo further evaluation.

VI. DEVELOPMENT OF A PHS INLINE SMOKEMETER AND COMPARISON OF INLINE AND END-OF-LINE OPACITY MEASUREMENT

Recent effort in the development of diesel smoke measurement devices has been directed, in part, toward inline-type smokemeters. As mentioned previously, at least one company (Atlantic Research) is marketing an inline instrument, and it seems likely that other companies will follow suit. Inline smokemeters enjoy two particular advantages over end-of-line instruments; namely, an inline smokemeter can be permanently mounted in a test cell installation, and the resulting closed exhaust system does not allow exhaust gases into the cell. These two features make inline smokemeters attractive to many research and testing groups.

However, inline opacity measurement is obviously based on physical conditions quite different from those of end-of-line measurement. For instance, the exhaust gases in the pipe are subject to different turbulences, pulsations, flow rates, and temperatures than the gases exiting the pipe. The effect of these differences on indicated opacity obtained in the line and at the end of the line is not fully known. The work in this section was a preliminary research effort in the correlation of inline and end-of-line sampling techniques. Also, under terms of this project contract, an identical inline smokemeter was constructed by SwRI and furnished to EPA for further tests and evaluation.

A. Design Criteria of the PHS Inline Smokemeter

The primary objective of this part of the project was to compare the opacity readings obtained with in-the-line and end-of-line sampling techniques. Hence, an inline smokemeter that correlated with the standard PHS end-of-line smokemeter was needed, and considerable effort was directed towards the development of such an inline instrument. The approach to this development work was to retain,as much as possible, the basic components (e.g., optical system, collimating tubes, and control-readout box) of the standard PHS smokemeter.

The criteria that the inline smokemeter design had to meet are the following. First, the inline instrument must have calibration accuracy (with neutral density filters) that is equal to, or better than the PHS end-of-line smokemeter. Second, the time response of the inline must be fast enough to follow rapid changes in smoke opacity. Third, the inline must not exhibit excessive (more than two percent) baseline drift after extended full-power engine operation, with the accompanying high exhaust flow rate and temperature. The first two criteria were not difficult to meet, as all of the inline models developed used the same optical system (lamp, lens, and photocell) and electrical circuitry (i.e., readout box) as the standard PHS instrument. Hence, all inline models tested showed the excellent calibration accuracy and response characteristics of the end-of-line unit. It was meeting the third criterion - - holding baseline drift to less than two percent of scale - - that caused most of the difficulty in developing the inline PHS smokemeter.

Baseline drift is usually caused by misalignment of the optical system (due to thermal distortion of the unit) and/or by the accumulation of carbon particles on the lens and photocell. In an effort to prevent these two undesirable effects, several inline designs were tested, with varying degrees of success, before the final design was developed. All of the inline models tested will be briefly described next.

B. Development of the Inline Smokemeter

The original inline model consisted of a 3-foot length of 4-inch diameter steel tubing with mounting pads for the collimating tubes (Figure 73). There was a 3/8-inch air gap between the collimating tubes and the main pipe. The purpose of the air gap was to partially damp out the severe pulsations in the exhaust flow of the Cummins NH-220 engine. However, the large (2-1/4 inch) holes in the central pipe allowed the exhaust gases to penetrate into the collimating tubes and hence coat the optical surfaces (lens and photocell) with a carbon deposit. The flow of purge air was increased to keep the optical surfaces clean, but the problem persisted. There was also considerable leakage of exhaust through the air gap and into the test cell.

The first modification consisted of covering the large holes in the four-in pipe with thin metal plates drilled with three-eighth in diameter holes for the light beam to pass through. These smaller holes reduced the maximum amount of light reaching the photocell and, hence, reduced the maximum photocell output. The output circuit in the readout-control box was modified by reducing its resistance. This increased the maximum output voltage to 10MV and thus permitted use of a standard strip chart recorder with 10MV span. A schematic of the modified output circuit is included as part of Appendix

The smaller light beam holes reduced the exhaust leakage into the test cell, but the exhaust pulsations still filled the collimating tubes and again coated the optical surfaces with carbon build-up. The next step was to fit a metal plate, drilled with a 1/4-inch light beam hole, into the end of each collimating tube. Carbon build-up on the optical surfaces was still present, though considerably reduced. However, the smokemeter experienced heat distortion that caused misalignment of the small light beam holes. This misalignment caused the light beam to strike the edge of the hole in the exhaust pipe and resulted in opacity readings about twice those of the end-of-line smokemeter.

To minimize heat distortion of the inline unit, the 4-inch steel pipe was replaced with a 15-inch length of 4-inch aluminum pipe with 1/4-inch wall thickness (Figure 74). The light beam hole remained at 3/8 inch, and the air gap between pipe and collimating tubes was decreased to 3/16 inch. Heat distortion was less with this configuration, but still caused the smokemeter

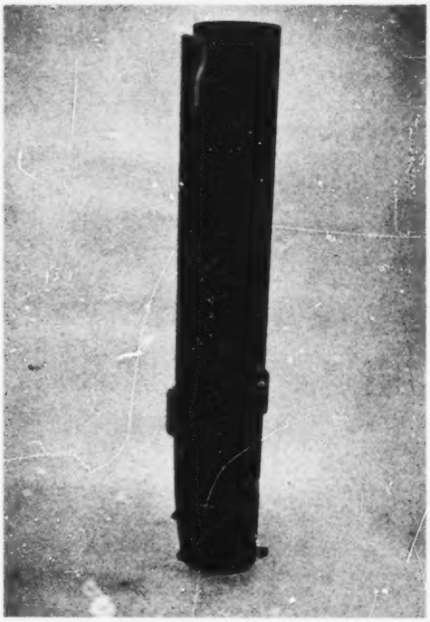


FIGURE 73. INITIAL PHS INLINE SMOKEMETER PIPE WITH MOUNTING FLANGE SHOWN

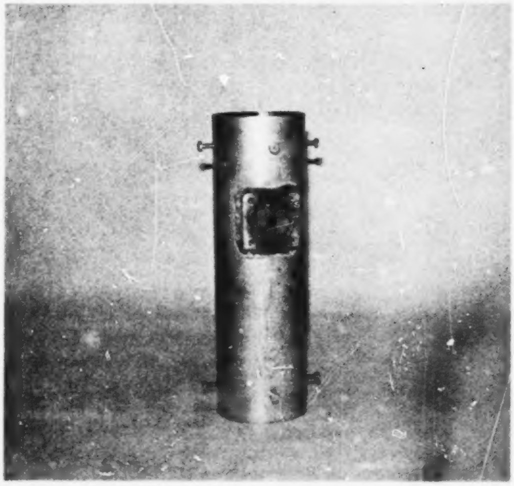


FIGURE 74. ALUMINUM INLINE SMOKEMETER PIPE-1/2-INCH LIGHT BEAM HOLE

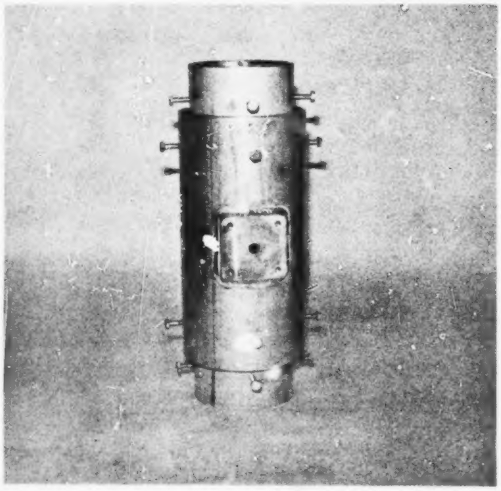


FIGURE 75. DUAL PIPE INLINE SMOKEMETER-SIDE VIEW

to read 10 to 15-percent opacity higher than the end-of-line instrument. Carbon build-up on the lens surface also contributed to these higher readings. To further reduce the effect of heat distortion, the holes in the aluminum pipe were drilled out to 1/2-inch. This step greatly reduced the effect of distortion, and the inline smokemeter registered about two-percent opacity higher than the end-of-line smokemeter. However, after about two minutes of full-load engine operation, the lens in the inline unit again became covered with carbon. The air gap was increased from 3/16-inch to 3/4-inch in hopes the exhaust would not penetrate into the collimating tubes. This was not successful, however, and it was decided to try a different inline design.

The next model consisted of a 4-inch aluminum pipe, identical to that described in the preceding paragraph, fitted inside a 5-inch aluminum pipe drilled with 1/2-inch light beam holes (Figures 75 and 76). There was, therefore, a 1/2-inch gap between the two pipes. This arrangement was to reduce heat transfer from the inner pipe to the outer, and hence to minimize heat distortion. Also, it was hoped the gap between the two pipes would help to damp out exhaust pulsations and hence prevent the exhaust from entering the collimating tubes. However, the performance of this model was worse than the preceding design. Opacity readings from this inline instrument were almost double those of the end-of-line unit, and carbon build-up on the lens was quite severe.

The next inline design consisted of a length of 4-inch diameter steel tubing drilled with 3/8-inch light beam holes and fitted into an aluminum bracket. A frame ring from the PHS end-of-line smokemeter was attached to this bracket and the collimating tubes were mounted on the ring in the usual manner (Figures 77 and 78). It was thought that this design would, by removing the collimating tubes from the immediate vicinity of the exhaust pipe, lessen the amount of exhaust entering the tubes and also minimize heat distortion. These objectives were accomplished in large measure, as the inline smokemeter read only about two-percent opacity higher than the end-of-line unit. The two smokemeters followed opacity changes during transient operation in a similar and consistent manner.

This inline configuration showed a slight (2- to 3-percent opacity) upward zero change after several minutes of full-load engine operation. This zero change was thought to be caused by a slight carbon build-up on the lens. Therefore, a small air jet made from 1/4-inch copper tubing was installed on each side of the exhaust pipe, at the rear of the light beam hole (Figure 79). The air from the jets was directed across these holes, at right angles to the escaping exhaust flow. It was thought the air jet would diffuse the exhaust flow as it left the pipe and thus keep it out of the collimating tubes. However, the zero change continued as before, and it was concluded that thermal distortion of the smokemeter frame was to blame. In addition, the opacity readings were sensitive to the amount of purge flowing through the external air jets. That is, if the air flow from these jets was "correct" for

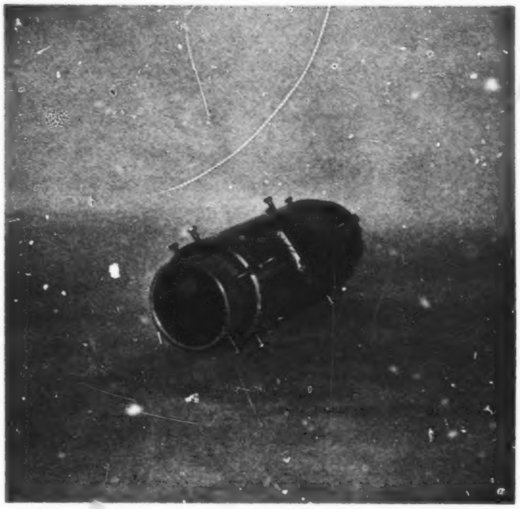


FIGURE 76. DUAL PIPE INLINE SMOKEMETER-END VIEW

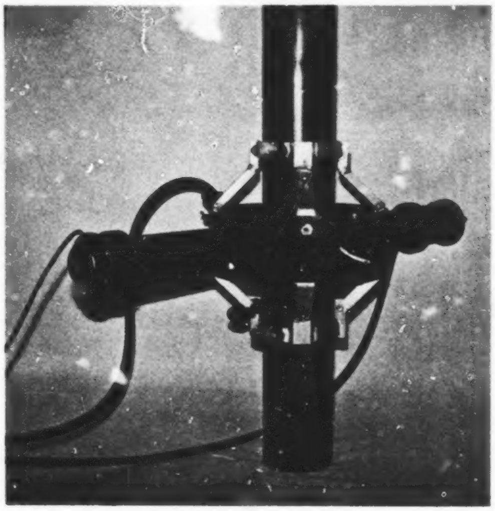


FIGURE 77. ADVANCED DESIGN PHS INLINE SMOKEMETER

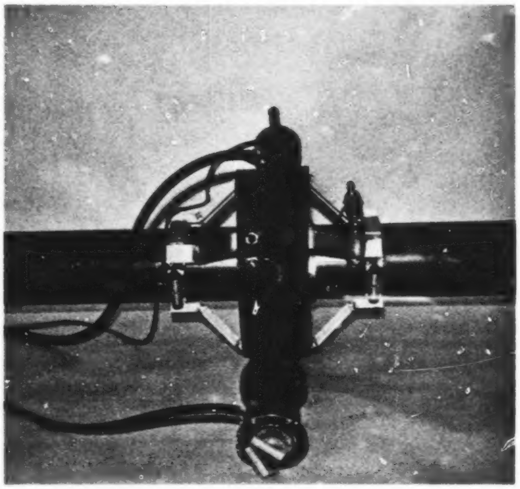


FIGURE 78. ADVANCED DESIGN PHS INLINE SMOKEMETER

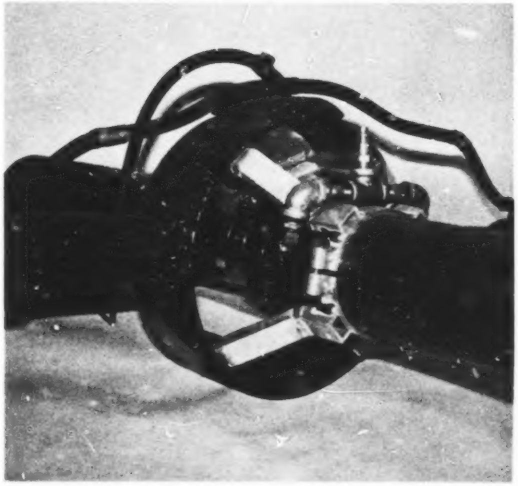


FIGURE 79. AIR JETS ON INLINE SMOKEMETER

a certain engine speed and load condition, the same air rate was not necessarily suitable for another engine condition, and indicated smoke opacity might be completely erroneous. No one air rate was found suitable for all engine conditions and opacity levels.

The next inline model represented a substantial departure from previous designs. Small metal tubes, approximately three in long by three-eights in ID, were welded to the light beam holes in the central exhaust pipe. The outer end of each tube was sealed with a small disc of clear glass epoxyed to the tube. Thus, the effect of this design change was to create a closed system. Purge air was admitted to each sealed tube by means of a one-quarter in OD copper tube inserted just ahead of the glass window.

This instrument was tested on a truck-tractor powered by a Cummins NHC-250 engine. The vehicle was operated on a chassis dynamometer. No exhaust leakage occurred under any test condition, and the glass "windows" remained clean with a purge air rate of three to four SCFM. No purge air was routed to the collimating tubes. These preliminary tests showed a substantial improvement over those of the previous inline design. However, a small amount of baseline change still existed. The inline smokemeter also tended to read progressively higher opacity (under steady-state conditions) with elapsed time.

It was thought that both of these anomalies were due to thermal distortion effects. Therefore, the next step was to construct the central four-in diameter exhaust pipe and the mounting bracket from stainless steel. The stainless steel components have less differential thermal expansion than the original components. Other improvements made at this time included replacement of the small sealed optical tubes with stainless versions, replacement of the epoxyed glass "windows" with screw-on caps containing the glass, and routing a small flow of purge air to the collimating tubes. This purge air served to keep the collimating tubes clear of any exhaust smoke that happened to recirculate in the vicinity of the smokemeter. This model of the inline instrument is shown in several views in Figure 80, and a schematic drawing of one of the sealed optical tubes is shown in Figure 81. General operating instructions for the inline smokemeter are contained in Appendix C.

In preliminary tests, this inline had approximately ± 1.0-percent opacity baseline change after extended running on the stationary NH-220 engine. This was considerably less change than previous inline models had shown, but was somewhat more than the typical PHS end-of-line demonstrates under similar conditions. The opacity traces from the two instruments showed the same general trends; i.e., when one smokemeter registered an increase (decrease) in smoke opacity, the other unit registered a similar increase (decrease). Also, the two smokemeters produced traces

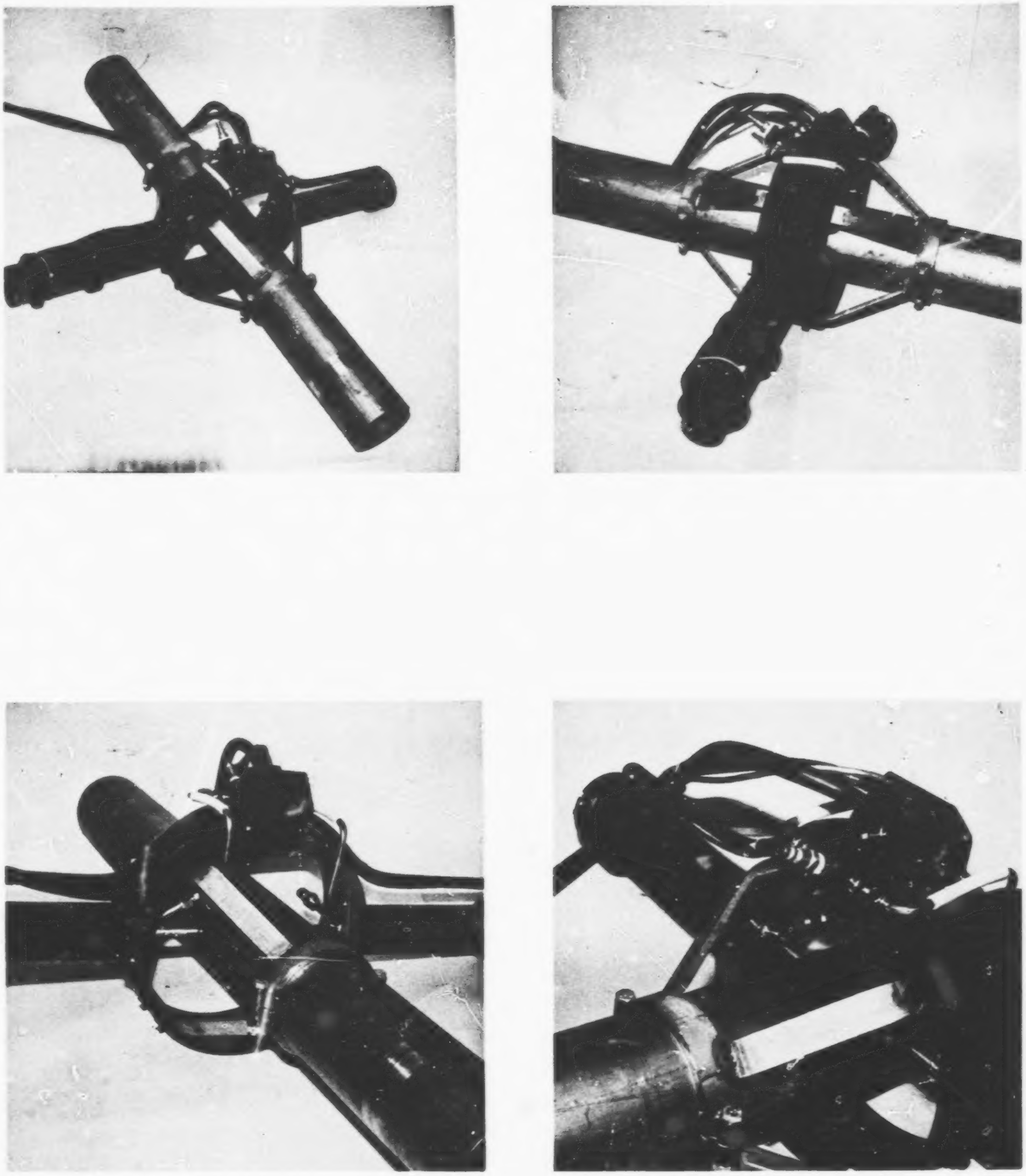


FIGURE 80. FINAL DESIGN OF THE PHS INLINE SMOKEMETER

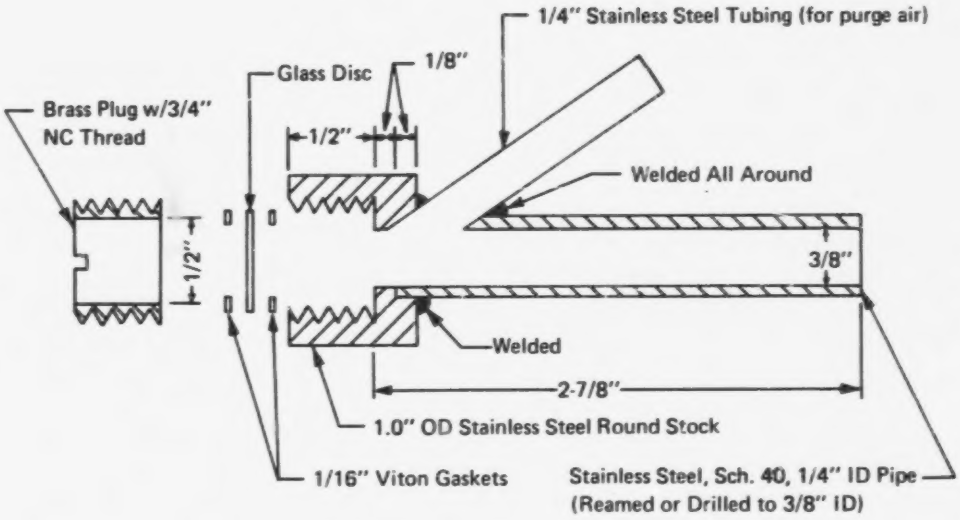

1/4" Stainless Steel Tubing (for purge air)
Glass Disc
1/8"
Brass Plug w/3/4" NC Thread
1/2"
Welded All Around
1/2"
3/8"
Welded
2-7/8"
1.0" OD Stainless Steel Round Stock
1/16" Viton Gaskets
Stainless Steel, Sch. 40, 1/4" ID Pipe (Reamed or Drilled to 3/8" ID)

FIGURE 81. SCHEMATIC DRAWING OF SEALED OPTICAL TUBE FROM PHS INLINE SMOKEMETER

of similar shape and duration for engine accelerations. In general, the opacity trace for the inline was slightly smoother, with less "hash", than the end-of-line trace. This difference was apparently due to less variation in exhaust flow passing through the inline than for the plume passing through the end-of-line instrument.

This final version of the inline smokemeter was tested on naturally aspirated Cummins NHC-250 and V-903 engines, and also on a turbocharged Mack ENDT 673B engine. These engines provided a wide range of smoke opacities, exhaust temperatures, and flow rates. The test procedure used was the simulated Federal smoke test. The "a" and "b" factors for these tests are given in Table 22, below.

TABLE 22. FEDERAL "a" AND "b" FACTORS BY INLINE AND END-OF-LINE OPACITY MEASUREMENT

Engine	"a" Factors, % Opacity		"b" Factors, % Opacity	
	E.O.L.	Inline	E.O.L.	Inline
Cummins	24.2	23.9	33.2	31.3
Cummins	18.3	15.2	21.7	17.4
Mack ENDT 673B	14.8	11.5	8.3	6.3

From Table 22, it can be seen that the inline instrument read two- to five-percent opacity lower than the end-of-line smokemeter in all of the tests. The best agreement between the two smokemeters occurred in the case of the Cummins NHC-250 engine. Slightly less agreement was obtained in the tests with the Cummins V-903 engine, and the two smokemeters showed the least correlation for the turbocharged Mack engine. In particular, the "b" factors for the V-903 engine were considerably different, as were the "a" factors of the 673B engine. Three opacity traces from these smoke tests are shown in Figures 82, 83, and 84. One figure is included for each of the three trucks used for the tests. The smoke trace evaluation sheets for these tests are contained in Appendix D. These sheets contain the individual opacity readings for each test sequence.

The fact that the inline smokemeter registered lower smoke opacity than the end-of-stack unit was not necessarily a discrepancy in the inline instrument itself, since there was no a prior reason why the two instruments should register the same opacity. What was judged important was that this inline model (1) calibrated with neutral density filters to a high degree of accuracy; (2) had response fast enough to follow transient smoke conditions; and (3) had an acceptable amount of baseline change after extended running time. In view of these facts, it was decided to proceed with the study of effect of exhaust variables on inline vs end-of-line sampling methods using this inline smokemeter.

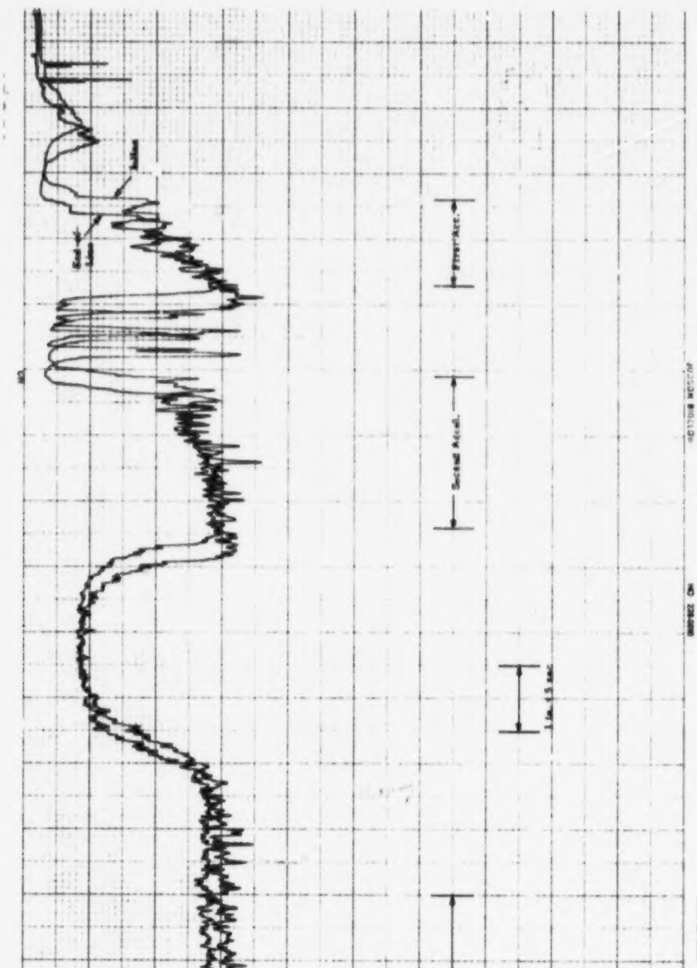


FIGURE 82. OPACITY TRACES FOR FEDERAL SMOKE TEST WITH PHS INLINE AND END-OF-LINE SMOKEMETERS - CUMMINS NHC-250 ENGINE

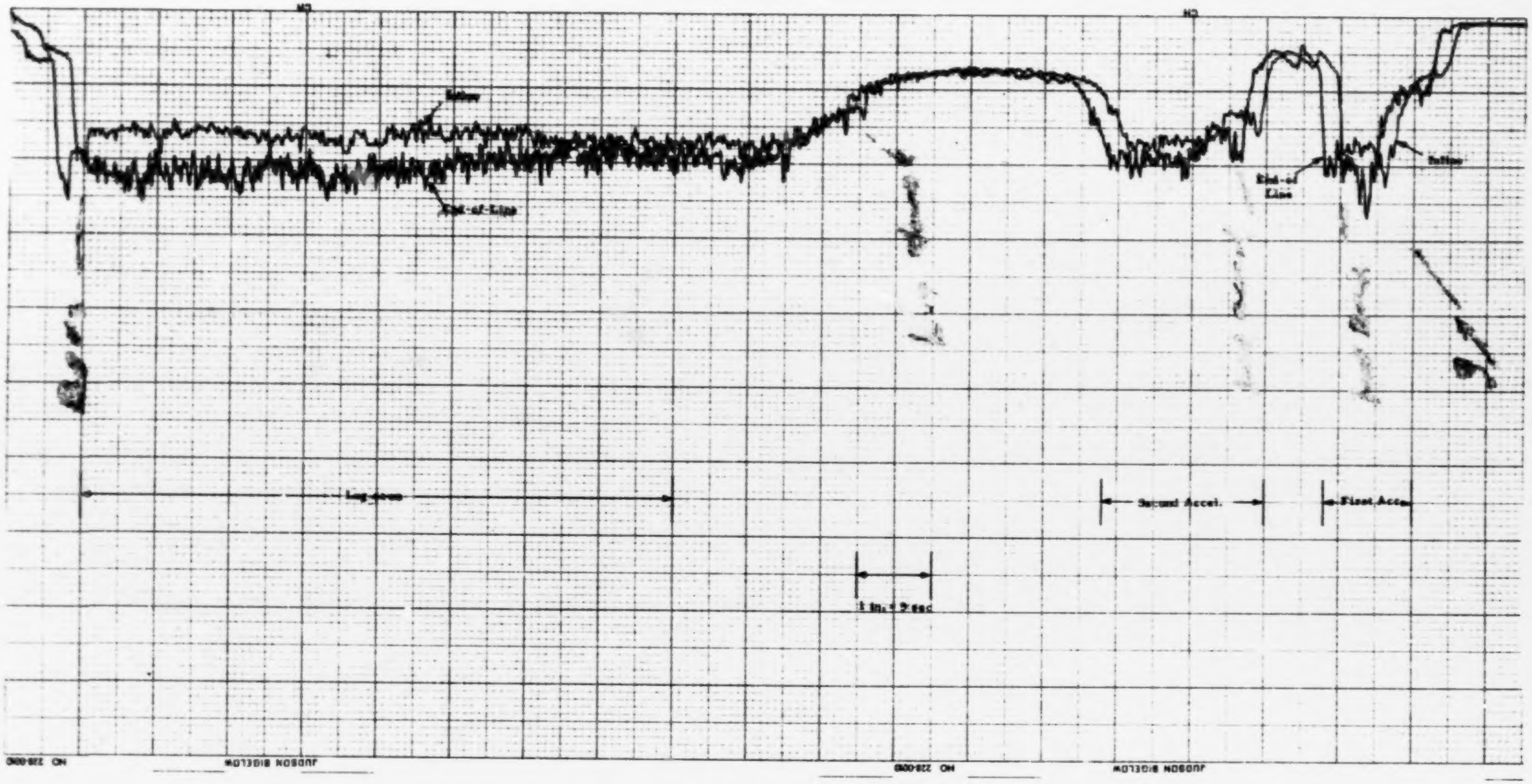


FIGURE 83. OPACITY TRACES FOR FEDERAL SMOKE TEST WITH PHS INLINE AND END-OF-LINE SMOKEMETERS - CUMMINS V-903 ENGINE

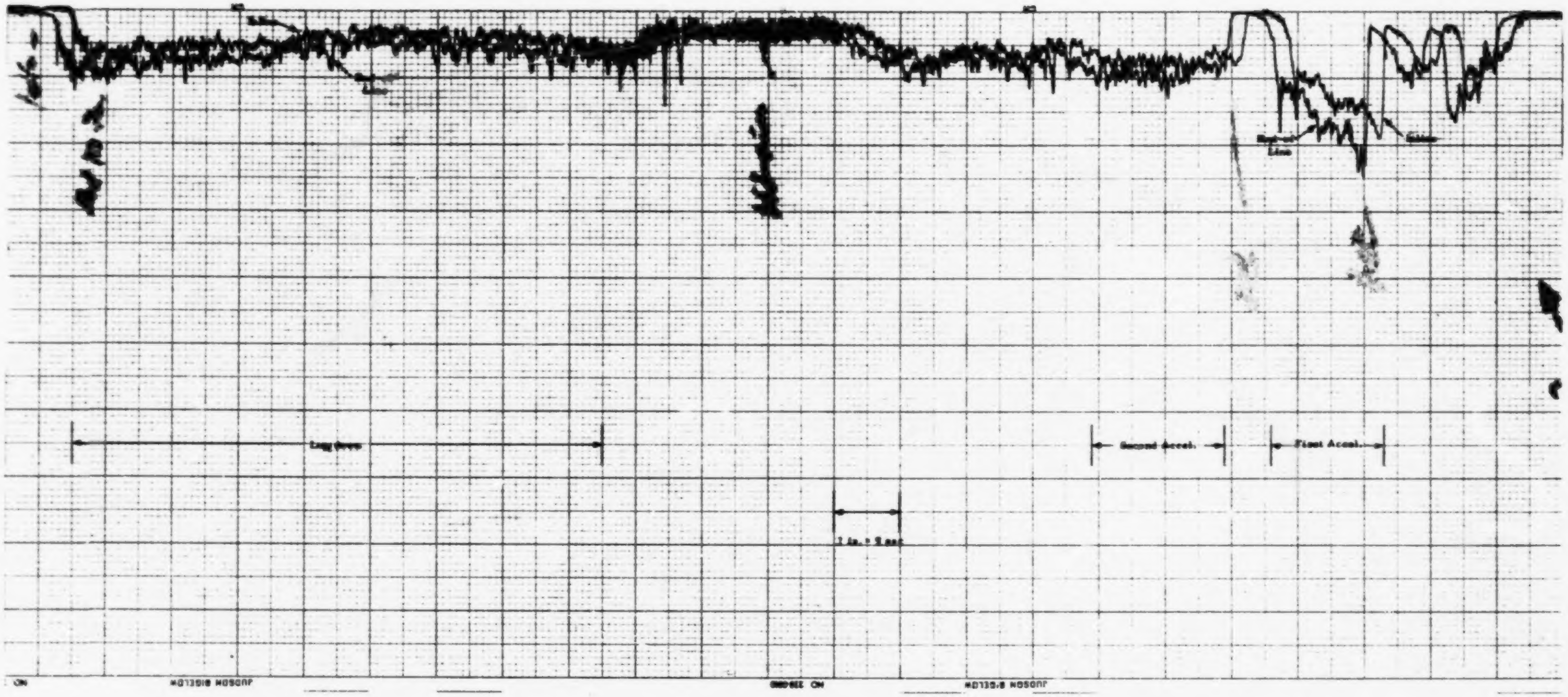


FIGURE 84. OPACITY TRACER FOR FEDERAL SMOKE TEST WITH PHS INLINE AND END-OF-LINE SMOKEMETERS - MACK ENDT 673B ENGINE

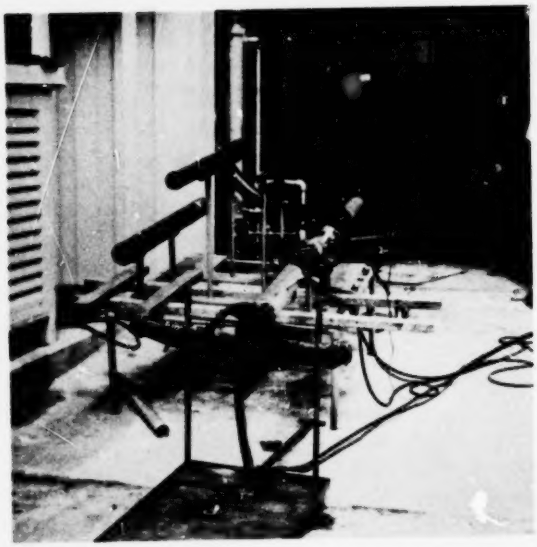
C. Effect of Exhaust Variables On Inline and End-of-Line Opacity Measurement

The stationary-mounted Cummins NH-220 engine was selected as the smoke generator for this phase of the inline study because of its highly pulsating flow and high exhaust temperatures. The inline and end-of-line smokemeters were placed in series in the exhaust system of the engine, with approximately three ft of pipe between them (Figure 85). A thermocouple was used to measure exhaust temperature at a point about one ft upstream from the inline instrument. The engine's intake system was partially restricted to increase the range of smoke opacities, and a nominal opacity level of some 60 percent was the highest thus obtained.

The test sequence consisted of a series of steady-state engine conditions at engine speeds of 600 rpm (low idle), 1500, 1800, and 2100 rpm. Engine loads at each speed were zero, full, and approximately one-third and two-thirds of full load. Three such sequences were performed in the study. The first and third sequences went from 1500 rpm and zero load to 2100 rpm and full load, in an increasing manner. The second sequence went from 2100 rpm and full load to 1500 rpm and zero load, in a decreasing manner. Two idle conditions were included in each test sequence, one between 1500 and 1800 rpm and the other between 1800 and 2100 rpm. For the first and third sequences, the idle conditions are "hot", since they follow full load at 1500 and 1800 rpm. The idle conditions for the second test sequence are "cold", since they follow zero load at 2100 and 1800 rpm.

The average data for the three test sequences are presented in Table 23. The data include the estimated exhaust flow rate (in cubic ft per min at line temperature and pressure) through the smokemeters and exhaust temperature at the inline instrument for each test condition, as well as the opacities registered by the two smokemeters. The absolute difference between the opacity readings of the two smokemeters is given in Table 23 in the column headed "Diff.".

The data in the table reveal that the inline and end-of-line instruments read within 1.0-percent opacity in a majority of the test conditions. At full engine load at 1500 and 2100 rpm, the end-of-stack smokemeter read 4.0- and 1.8-percent opacity higher, respectively, than the inline. However, at full power at 1800 rpm, the inline instrument read 0.5-percent opacity higher than the end-of-line. The maximum deviation at 1800 rpm was 3.0-percent opacity at one-third and two-thirds of full load. It is not known why the readings differed most at these part-load conditions rather than at full load. The opacity readings at 1800 rpm were also unusual in that the inline read higher than the end-of-line at all four conditions. Again, the cause is not known, although it is possible that a peculiar resonance condition existed in the exhaust pipe at 1800 rpm and caused the inline smokemeter to register higher opacities. The problem of determining resonance conditions in the



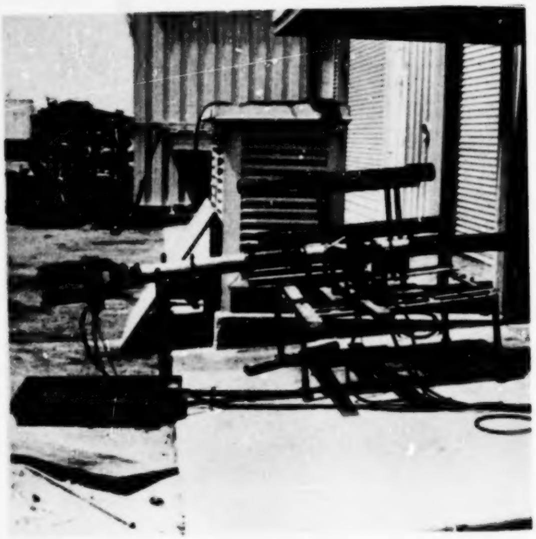


FIGURE 85. INLINE AND END-OF-LINE SMOKEMETERS ON TEST STAND

TABLE 23. COMPARISON OF INLINE AND END-OF-LINE OPACITY READINGS UNDER STEADY-STATE SMOKE CONDITIONS

Engine RPM	Engine Load	Exhaust Flow Rate, ACFM	Nominal Exhaust Temp., °F	Smoke Opacity, %		
				E.O.L.	Inline	Diff.
1500	0	364	360	2.7	2.5	0.2
"	1/3	566	815	11.2	12.2	1.0
"	2/3	688	1090	32.0	31.2	0.8
"	Full	734	1195	50.7	46.7	4.0
1800	0	478	440	3.2	4.1	0.9
"	1/3	680	820	10.5	13.5	3.0
"	2/3	802	1050	23.0	26.0	3.0
"	Full	930	1290	46.0	46.5	0.5
2100	0	544	565	4.7	5.0	0.3
"	1/3	716	890	13.7	12.8	0.9
"	2/3	921	1275	30.7	30.3	0.4
"	Full	956	1340	59.3	57.5	1.8
600*	0	192	330	3.0	2.4	0.6
"**	0	174	260	2.0	1.5	0.5
				Average Difference		1.3

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*Hot idle following full load.

**Cold idle following zero load.

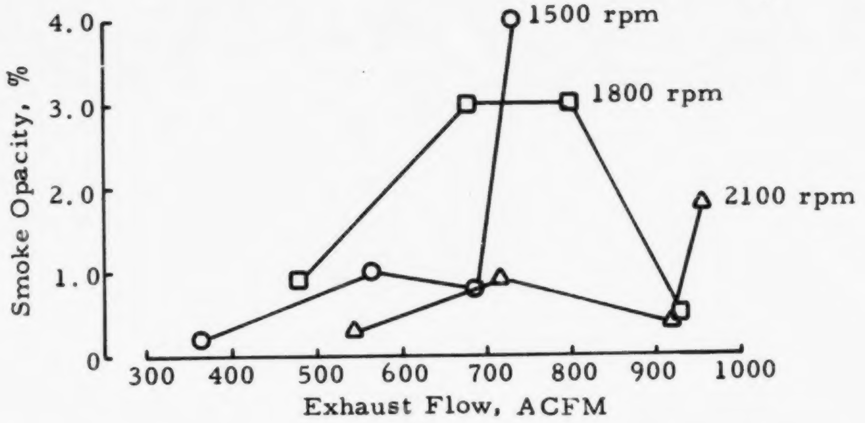

FIGURE 86. ABSOLUTE DIFFERENCE BETWEEN PHS INLINE AND END-OF-LINE OPACITY READINGS AS A FUNCTION OF EXHAUST FLOW RATE

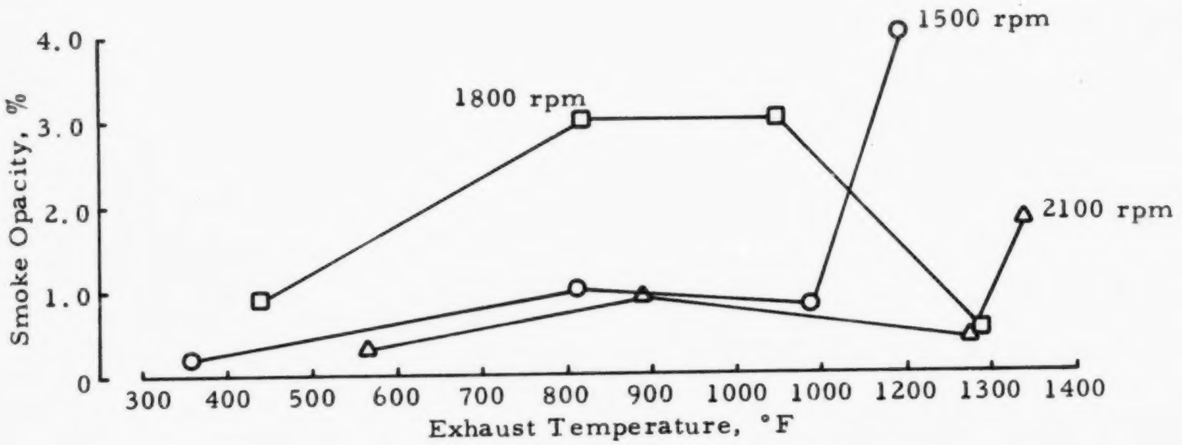

FIGURE 87. ABSOLUTE DIFFERENCE BETWEEN PHS INLINE AND END-OF-LINE OPACITY READINGS AS A FUNCTION OF EXHAUST TEMPERATURE

pipe and their effect on opacity measurement is extremely complex and certainly beyond the scope of this project. However, there is little doubt that such conditions do influence the readings of the inline instrument.

The two smokemeters produced opacity readings within 1.0-percent opacity during both "hot" and "cold" idles. However, the opacities were slightly higher for the "hot" idle. Whether the "hot" exhaust is actually of higher opacity than the "cold" exhaust, or whether the higher temperature is producing a thermal effect in the two smokemeters, is not known.

The absolute difference (in percent opacity) in the readings of the two instruments is graphed as a function of exhaust volumetric flow rate and exhaust temperature in Figures 86 and 87, respectively. Since the volumetric flow rate is, for a given engine speed, a function of the exhaust temperature, the two figures differ only in the scale of their respective abscissas. The four data points for each engine speed that are shown in these figures are, of course, the four load points of the engine at each speed, with the zero-load points appearing at the far left of the figures and the full-load points at the far right.

Figures 86 and 87 reflect the previous discussion of the data in Table 23. That is, the opacity readings of the two smokemeters tend to diverge when going from zero load to one-third load, then tend to converge or maintain the same agreement between one-third and two-thirds of full load. The difference in the two opacity readings increases sharply at full load at 1500 and 2100 rpm, and decreases sharply at 1800 rpm and full load. Although the behavior of the two smokemeters is inconsistent in this regard, it can at least be said that the full-load conditions, with their accompanying high flow rates and high temperatures, produce the most drastic changes in the instruments' opacity readings. However, the agreement between the two smokemeters is, on the average, quite good.

VII. SUMMARY AND CONCLUSIONS

This project has covered several areas of interest in the measurement of diesel smoke opacity. Several smoke test procedures, intended for in-use vehicle inspections, were compared to a chassis dynamometer version of the Federal smoke compliance test. Several commercially-available smokemeters had their performance compared to that of the standard PHS end-of-line smokemeter. Special topics that were investigated were the comparison of opacity measurements from three identical PHS smokemeters and the correlation of the standard 10-in diameter PHS smokemeter with enlarged versions of 20-in and 40-in diameter. Finally, an inline version of the PHS smokemeter was developed at SwRI for this project. Inline and end-of-line opacity measurements were made simultaneously in order to determine the correlation between the two measurement techniques and also to determine the effect of certain exhaust variables, such as flow rate and temperature, on this correlation.

The following conclusions were drawn from the results of the items of work mentioned above:

(1) None of the smoke test procedures correlated well with the simulated Federal smoke test for all engine/vehicle combinations used in the evaluation study. The experimental SwRI procedure came closest to duplicating the results of the simulated Federal test in the largest number of cases, while the New Jersey truck and bus procedures in general showed poor correlation with the Federal test. However, the New Jersey procedures appear to be related to regular in-service operation of diesel-powered trucks and buses, and thus fulfill a principal requirement for an inspection-type test procedure.

(2) Based on the results of the bench tests, the Atlantic Research smokemeter performed best, while the results of the various smoke tests indicate the Bacharach and Atlantic Research were approximately equal in their performance. In all cases the Nebetco instrument was far behind. Neither the Atlantic Research or Bacharach correlated with the PHS smokemeter in all the smoke tests performed.

(3) Use of three typical PHS smokemeters in a series of smoke tests showed that excellent correlation existed between the three instruments. These tests also confirmed that pipe diameter has a definite effect on indicated smoke opacity; i.e., the larger the diameter, the higher the opacity registered by the smokemeter. However, the Beere-Lambert law was quite effective in correlating the measured opacities for the various pipe diameters.

(4) The special enlarged versions of the PHS smokemeter, of 20- and 40-in diameter, produced nominal opacity readings that were very close to those of the standard ten-in diameter instrument. Thus, the increased light

beam path length of the enlarged smokemeters had little or no effect on indicated smoke opacity, at least for this series of tests using three-in and four-in diameter pipe. However, the amount of "hash" in the opacity traces increased substantially with the larger diameter instruments.

(5) The Atlantic Research inline smokemeter produced substantially different opacity readings from the PHS end-of-line instrument. The amount of this difference decreased as the exhaust pipe diameter was increased from three in to four in to five in. Correction of opacities from one pipe size to another by means of the Beere-Lambert law was only partially successful.

(6) The PHS inline smokemeter designed and constructed in the course of this project displayed a reasonable degree of correlation with the PHS end-of-line smokemeter during steady-state smoke tests. However, the correlation between the two instruments during simulated Federal smoke tests with three truck-tractors was inconsistent, showing good agreement in some instances and poor agreement in others. In either case, the PHS inline read much closer to the standard PHS smokemeter than did the Atlantic Research inline instrument.

(7) The steady-state smoke tests performed with the inline and end-of-line PHS smokemeters on a Cummins NH-220 engine showed that varying exhaust flow rates and temperatures produced different changes in the two instruments' opacity readings, causing them to converge in some cases and to diverge in others. However, in most instances this observed convergence or divergence was of small magnitude.

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APPENDIX A

FEDERAL SMOKE TEST PROCEDURE
(FEDERAL REGISTER, VOL. 35, NO. 219, NOV. 10, 1970)

A-2.

FEDERAL REGISTER

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Tuesday, November 10, 1970 • Washington, D.C.

PART II

Department of Health, Education, and Welfare

Office of the Secretary

•

Control of Air Pollution From New Motor Vehicles and New Motor Vehicle Engines

122

Subpart J—Test Procedures for Engine Exhaust Emissions (Heavy Duty Diesel Engines)

§ 85.120 Introduction.

(a) The procedures described in this subpart will be the test program to determine the conformity of heavy duty diesel engines with the applicable standards set forth in this part:

(b) The test consists of a prescribed sequence of engine operating conditions on an engine dynamometer with continuous examination of the exhaust gases. The test is applicable equally to controlled engines equipped with means for preventing, controlling, or eliminating smoke emissions and to uncontrolled engines.

(c) The test is designed to determine the opacity of smoke in exhaust emissions during those engine operating conditions which tend to promote smoke from diesel-powered vehicles.

(d) The test procedure begins with a warm engine which is then run through preloading and preconditioning operations. After an idling period, the engine is operated through acceleration and lugging modes during which smoke emission measurements are made to compare with the standards. The engine is then returned to the idle condition and the acceleration and lugging modes are repeated. Three sequences of acceleration and lugging constitute the full set of operating conditions for smoke emission measurement.

§ 85.121 Diesel fuel specifications.

(a) The diesel fuels employed shall be clean and bright, with pour and cloud points adequate for operability. The fuels may contain nonmetallic additives as follows: cetane improver, metal deactivator, antioxidant, dehazer, antirust, pour depressant, dye, and dispersant.

(b) Fuel meeting the following specifications, or substantially equivalent specifications approved by the Secretary, shall be used in exhaust emission testing. The grade of fuel recommended by the engine manufacturer, commercially designated as "Type 1-D" or "Type 2-D", shall be used.

Item	ASTM test method No.	Type 1-D	Type 2-D
Cetane	D 613	48-54	42-50
Distillation range	D 86		
IBP, °F		330-390	340-400
10 percent point, °F		370-430	400-460
50 percent point, °F		410-480	470-540
90 percent point, °F		460-520	550-610
EP, °F		500-560	580-660
Gravity, ° API	D 287	40-44	33-37
Total sulfur, percent	D 129 or D 2622	0.05-0.20	0.2-0.5
Hydrocarbon composition	D 1319		
Aromatics, percent		8-15	27 (Min.)
Paraffins, Naphthenes. Olefins		Remainder	Remainder
Flash point, °F (Min.)	D 93	120	130
Viscosity, centistokes	D 445	1.6-2.0	2.0-3.2

(c) Fuel meeting the following specifications, or substantially equivalent specifications approved by the Secretary, shall be used in service accumulation. The grade of fuel recommended by the engine manufacturer, commercially designated as "Type 1-D" or "Type 2-D", shall be used.

Item	ASTM test method No.	Type 1-D	Type 2-D
Cetane	D 613	48-54	42-55
Distillation range	D 86		
IBP, °F		330-390	340-410
10 percent point, °F		370-430	400-470
50 percent point, °F		410-480	470-540
90 percent point, °F		460-520	550-610
EP, °F		500-560	580-660
Gravity, °API	D 287	40-44	33-40
Total sulfur, percent	D 129 or D 2622	0.05-0.20	0.2-0.5
Flash point, °F (Min.)	D 93	120	130
Viscosity, centistokes	D 445	1.6-2.0	2.0-3.2

(d) The type fuel, including additive and other specifications, used under paragraphs (b) and (c) of this section shall be reported in accordance with § 85.51(b)(3).

§ 85.122 Dynamometer operation cycle for smoke emission tests.

(a) The following sequence of operations shall be performed during engine dynamometer testing of smoke emissions, starting with the dynamometer preloading determined and the engine preconditioned (§ 85.127(c)).

(1) *Idle mode.* The engine is caused to idle for 5 to 5.5 minutes at the manufacturer's recommended low idle speed. The dynamometer controls shall be set to provide minimum load by turning the load switch to the "off" position or by adjusting the controls to the minimum load position.

(2) *Acceleration mode.* (i) The engine speed shall be increased to 200±50 r.p.m. above the manufacturer's recommended low idle speed within 3 seconds.

(ii) The engine shall be accelerated at full-throttle against the inertia of the engine and dynamometer or alternately against a preselected dynamometer load such that the engine speed reaches 85 to 90 percent of rated speed in 5±1.5 seconds.

(iii) When the engine reaches the speed required in subdivision (ii) of this subparagraph, the throttle shall be moved rapidly to the closed position and the preselected load required to perform the acceleration in subdivision (iv) of this subparagraph shall be applied. The engine speed shall be reduced to the speed of maximum rated torque or 60 percent of rated speed (whichever is higher), with ±50 r.p.m. Smoke emissions during this transitional mode are not used in determining smoke emissions to compare with the standard.

(iv) The throttle shall be moved rapidly to the full-throttle position and the engine accelerated against the preselected dynamometer load such that the engine speed reaches 95 to 100 percent of rated speed in 10±2 seconds.

(3) *Lugging mode.* (i) Proceeding from the acceleration mode, the dynamometer controls shall be adjusted to permit the engine to develop maximum horsepower at rated speed. Smoke emissions during this transitional mode are not used in determining smoke emissions to compare with the standard.

(ii) Without changing the throttle position, the dynamometer controls shall be adjusted gradually to slow the engine to the speed of maximum torque or to 60 percent of rated speed, whichever is higher. This engine lugging operation shall be performed smoothly over a period of 35±5 seconds. The rate of slowing of the engine shall be linear, within ±100 r.p.m.

(4) *Engine unloading.* After completion of the lugging mode in subparagraph (3)(ii) of this paragraph, the dynamometer and engine shall be returned to the idle condition described in subparagraph (1) of this paragraph.

(b) The procedures described in paragraph (a) (1) through (4) of this section shall be repeated until the entire cycle has been run three times.

§ 85.123 Dynamometer and engine equipment.

The following equipment shall be used for smoke emission testing of engines on engine dynamometers.

(a) An engine dynamometer with adequate characteristics to perform the test cycle described in § 85.122.

(b) An engine cooling system having sufficient capacity to maintain the engine at normal operating temperatures during conduct of the prescribed engine tests.

(c) A noninsulated exhaust system extending 12±2 feet from the exhaust manifold of the engine and presenting an exhaust back pressure within ±0.2 inches Hg of the upper limit at maximum rated horsepower, as established by the engine manufacturer in his sales and service literature for vehicle application. A conventional automotive muffler of a size and type commonly used with the engine being tested shall be employed in the exhaust system during smoke emission testing. The terminal 2 feet of the exhaust pipe shall be of circular cross section and be free of elbows and bends. The end of the pipe shall be cut off squarely. The terminal 2 feet of the exhaust pipe shall have a diameter in accordance with the engine being tested, as specified below:

Maximum rated horsepower	*Exhaust pipe size*
Less than 101	2''
101–200	3''
201–300	4''
301 or more	5''

(d) An engine air inlet system presenting an air inlet restriction within ±1-inch of water of the upper limit for the engine operating condition which results in maximum air flow, as established by the engine manufacturer in his sales and service literature, for the engine being tested.

§ 85.124 Smoke measurement system.

(a) *Schematic drawing.* The following figure (fig. 7) is a schematic drawing of the optical system of the light extinction meter.

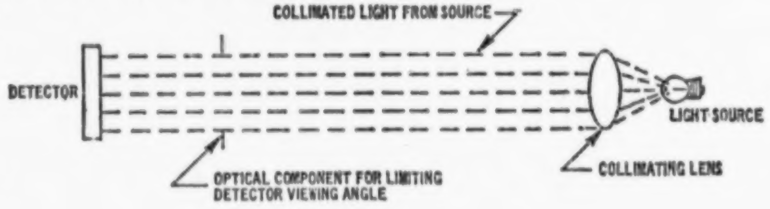

COLLIMATED LIGHT FROM SOURCE
DETECTOR
LIGHT SOURCE
OPTICAL COMPONENT FOR LIMITING DETECTOR VIEWING ANGLE
COLLIMATING LENS

Figure. 7. USPHS smokemeter optical system (schematic).

(b) *Equipment.* The following equipment shall be used in the system:

(1) Adapter—the smokemeter optical unit may be mounted on a fixed or movable frame. The normal unrestricted shape of the exhaust plume shall not be modified by the adapter, the meter, or any ventilation system used to remove the exhaust from the test site.

(2) Smokemeter (light extinction meter)—continuous recording, full-flow light obscuration meter. It shall be positioned near the end of the exhaust pipe so that a built-in light beam traverses the exhaust smoke plume which issues from the pipe at right angles to the axis of the plume. The light source is an incandescent lamp operated at a constant voltage of not less than 15 percent of the manufacturer's specified voltage. The lamp output is collimated to a beam with a nominal diameter of 1.125 inches. The angle of divergence of the collimated beam shall be within 4° included angle. A light detector, directly opposed to the light source, measures the amount of light blocked by the smoke in the exhaust. The detector sensitivity is restricted to the visual range and comparable to that of the human eye. A collimating tube with apertures equal to the beam diameter is attached to the detector. It restricts the viewing angle of the detector to within 16° included angle. An amplified signal corresponding to the amount of light blocked is recorded continuously on a remote recorder. An air curtain across the light source and detector window assemblies may be used to minimize deposition of smoke particles on those surfaces provided that it does not measurably affect the opacity of the plume. The meter consists of two units, an optical unit and a remote control unit. Light extinction meters employing substantially identical measurment principles and producing substantially equivalent results but which employ other electronic and optical techniques may be used only after having been approved in advance by the Secretary.

(3) Recorder—a continuous recorder, with variable chart speed over a minimal range of 0.5 to 8.0 inches per minute (or equivalent) and an automatic marker indicating 1-second intervals shall be used for continuously recording the transient conditions of exhaust gas opacity, engine r.p.m. and torque. The recorder scale for opacity shall be linear and calibrated to read from 0 to 100 percent opacity full scale. The opacity trace shall have a resolution within 1 percent opacity. The recorder scale for engine r.p.m. and the recorder scale for observed engine torque shall be linear and shall have full scale calibration such as to facilitate chart reading. The r.p.m. trace shall have a resolution within 30 r.p.m. The torque trace shall have a resolution within 10 lb.-ft. Any means other than strip chart recorder may be used provided it produces a permanent visual data record of quality equal to or better than that described above.

(4) The recorder used with the smokemeter shall be capable of full-scale deflection in 0.5 second or less. The smokemeter-recorder combination may be damped so that signals with a frequency higher than 10 cycles per second are attenuated. A separate low-pass electronic filter with the following performance characteristics may be installed between the smokemeter and the recorder to achieve the high-frequency attenuation.

(i) 3 decibel point—10 cycles per second.

(ii) Insertion loss-zero ±0.5 decibels.

(iii) Selectivity—12 decibels per octave above 10 cycles per second.

(iv) Attenuation—27 decibles down at 40 cycles per second minimum.

(c) *Assembling equipment.* (1) The optical unit of the smokemeter shall be mounted radially to the exhaust pipe so that the measurement will be made at right angles to the axis of the exhaust plume. The distance from the optical centerline to the exhaust pipe outlet shall be 1.0 to 1.5 pipe diameters but never less than 4 inches. The full flow of the exhaust stream shall be centered between the source and detector apertures (or windows and lenses) and on the axis of the light beam.

(2) Power shall be supplied to the control unit of the smokemeter in time at least 15 minutes prior to testing to allow for stabilization.

§ 85.125 Information to be recorded.

The following information shall be recorded with respect to each test:

(a) Test number.

(b) Date and time of day.

(c) Instrument operator.

(d) Engine operator.

(e) Engine Identification numbers—Date of manufacture—Number of hours of operation accumulated on engine—Engine Family—Exhaust pipe diameter—Fuel injector type—Maximum measured fuel rate at maximum measured torque and horsepower—Air aspiration system—Low idle r.p.m.—Maximum governed r.p.m.—Maximum measured horsepower at r.p.m.—Maximum measured torque at r.p.m.—Exhaust system back pressure—Air inlet restriction.

(f) Smokemeter. Number—Zero control setting—Calibration control setting—Gain.

(g) Recorder chart. Identify zero traces—Calibration traces—Idle traces—Acceleration and lug-down test traces—Start and finish of each test.

(h) Ambient temperature in dynamometer testing room.

(i) Engine intake air temperature and humidity.

(j) Barometric pressure.

(k) Observed engine torque.

§ 85.126 Instrument checks.

(a) The smokemeter shall be checked according to the following procedure prior to each test:

(1) The optical surfaces of the optical section shall be checked to verify that they are clean and free of foreign material and fingerprints.

(2) The zero control shall be adjusted under conditions of "no smoke" to give a recorder trace of zero.

(3) Calibrated neutral density filters having approximately 20 percent and 40 percent opacity shall be employed to check the linearity of the instrument. The filter(s) shall be inserted in the light path perpendicular to the axis of the beam and adjacent to the opening from which the beam of light from the light source emanates, and the recorder response shall be noted. The nominal opacity valve of the filter will be confirmed by the Secretary. Deviations in excess of 1 percent of the nominal opacity shall be corrected.

(b) The instruments for measuring and recording engine r.p.m., engine torque, air inlet restrictions, exhaust system back pressure, etc., which are used in the tests prescribed herein shall be calibrated from time to time in accordance with good technical practice.

§ 85.127 Test run.

(a) The temperature of the air supplied to the engine shall be between 68° F. and 86° F. The observed barometric pressure shall be between 28.5 inches and 31 inches Hg. Higher air temperature or lower barometric pressure may be used, if desired, but no allowance will be made for possible increased smoke emissions because of such conditions.

(b) The governor and fuel system shall have been adjusted to provide engine performance at the levels specified by the engine manufacturer for maximum rated horsepower and maximum rated torque. These specifications shall be reported in accordance with § 85.51 (b)(3).

(c) The following steps shall be taken for each test:

(1) Start cooling system.

(2) Starting with a warmed engine, determine by experimentation the dynamometer inertia and dynamometer load required to perform the acceleration in the dynamometer cycle for smoke emission tests (§ 85.122(a)(2)). In a manner appropriate for the dynamometer and controls being used, arrange to conduct the acceleration mode.

(3) Install smokemeter optical unit and connect it to the recorder. Connect the engine r.p.m. and torque sensing devices to the recorder.

(4) Turn on purge air to the optical unit of the smokemeter, if purge air is used.

(5) Check and record zero and span settings of the smokemeter recorder at a chart speed of approximately 1 inch per minute. (The optical unit shall be retracted from its position about the exhaust stream if the engine is left running.)

(6) Precondition the engine by operating it for 10 minutes at maximum rated horsepower.

(7) Proceed with the sequence of smoke emission measurements on the engine dynamometer as prescribed in § 85.122.

(8) During the test sequence of § 85.122, continuously record smoke measurements, engine r.p.m. and torque at a chart speed of approximately 1 inch per minute minimum during the idle mode and transitional modes and 8 inches per minute minimum during the acceleration and lugging modes.

(9) Turn off engine.

(10) Check zero and reset if necessary and check span of the smokemeter recorder by inserting neutral density filters. If either zero or span drift is in excess of 2 percent opacity, the test results shall be invalidated .

§ 85.128 Chart reading.

(a) The following procedure shall be employed in reading the smokemeter recorder chart.

(1) Locate the acceleration mode (§ 85.122(a)(2)) and the lugging mode (§ 85.122(a)(3)) on the chart. Divide each mode into ½-second intervals beginning at the start of each mode Determine the average smoke reading during each ½-second interval except those recorded during the transitional portions of the acceleration mode (§ 85.122(a)(2)(iii)) and the lugging mode (§ 85.122(a)(3)(i)).

(2) Locate and record the 15 highest ½-second readings during the acceleration mode of each dynamometer cycle.

(3) Locate and record the five highest ½-second readings during the lugging mode of each dynamometer cycle.

§ 85.129 Calculations.

(a) Average the 45 readings in § 85.128 (a)(2) and designate the value as "a".

(b) Average the 15 readings in § 85.128 (a)(3) and designate the value as "b".

§ 85.130 Test engines.

(a) The engines covered by the application for certification will be divided into engine families based upon the criteria outlined in § 85.89(a).

(b) Emission data engines:

(1) Engines will be chosen to be run for emission data based upon engine family groupings. Within each engine family, the requirements of this paragraph must be met.

(2) Engines of each engine family will be divided into groups based upon exhaust emission control system. Two engines of each engine-system combination shall be run for smoke emission data as prescribed in § 85.132(b). Within each combination, the engines that feature the highest fuel feed per stroke, primarily at the speed of maximum rated torque and secondarily at rated speed, will be selected. In the case where more than one engine in an engine-system combination have the highest fuel feed per stroke, the engine with the highest maximum rated torque will be selected.

(c) Durability data engines:

(1) One engine from each engine-system combination shall be tested for lifetime smoke emission data as prescribed in § 85.132(c). Within each combination, the engine which features the highest fuel feed per stroke, primarily at rated speed and secondarily at the speed of maximum rated torque, will be selected for durability testing. In the case where more than one engine in an engine-system combination has the highest fuel feed per stroke, the engine with the highest maximum rated horsepower will be selected for durability testing.

(2) A manufacturer may elect to operate and test additional engines to represent any engine-system combination. The additional engines must be of the same model and fuel system as the engine selected in accordance with the provisions of subparagraph (1) of this paragraph. Notice of an intent to test additional engines shall be given to the Secretary not later than 30 days following notification of the test fleet selection.

(d) Any manufacturer whose projected sales of new motor vehicle engines subject to this subpart for the model year for which certification is sought is less than 200 engines may request a reduction in the number of test engines determined in accordance with the foregoing provisions of this section. The Secretary may agree to such lesser number as he determines would meet the objectives of this procedure.

(e) In lieu of testing an emission data or durability data vehicles elected under paragraph (b) or (c) of this section and submitting data therefor, a manufacturer may, with the prior written approval of the Secretary, submit data on a similar vehicle for which certification has previously been obtained.

§ 85.131 Maintenance.

(a) (1) Maintenance on the engines and fuel systems of durability engines may be performed only under the following provisions:

(i) One major engine servicing to manufacturer's specifications may be performed at 500 hours (±8 hours) of dynamometer operation. A major engine servicing shall be restricted to the following:

(*a*) Adjust low idle speed.
(*b*) Adjust valve lash if required.
(*c*) Adjust injector timing.
(*d*) Adjust governor.
(*e*) Clean and service injector tips.

(ii) Injectors may be changed if a persistent misfire is detected.

(iii) Normal engine lubrication services (engine oil change and oil filter, fuel filter, and air filter servicing and adjustment of drive belt tension, and engine bolt torque as required) will be allowed at manufacturer's recommended intervals.

(iv) Readjustment of the engine fuel rates may be performed only if there is a problem of dropping below 95 percent of maximum rated horsepower at 95–100 percent rated speed.

(v) Leaks in the fuel system, engine lubrication system and cooling system may be repaired.

(vi) Any other engine or fuel system maintenance or repairs will be allowed only with the advanced approval of the Secretary.

(2) Allowable maintenance on emission data engines shall be limited to the adjustment of engine low idle speed at the 125-hour test point.

(b) Complete emission tests (see §§ 85.121–85.129) shall be run before and after any engine maintenance which may reasonably be expected to affect emissions. These test data shall be supplied to the Secretary immediately after the tests, along with a complete record of all pertinent maintenance, including an engineering report of any malfunction diagnosis and the corrective action taken. In addition, all test data and maintenance reports shall be compiled and provided to the Secretary in accordance with § 85.53.

(c) If the Secretary determines that maintenance or repairs performed have resulted in a substantial change to the engine-system combination, the engine shall not be used as a durability data engine.

§ 85.132 Service accumulation and emission measurements.

Service accumulation shall be accomplished by operation of an engine on a dynamometer.

(a) Emission data engines: Each engine shall be operated on a dynamometer for 125 hours with the dynamometer and engine adjusted so that the engine is operating at 95–100 percent of rated speed and at least 95 percent of maximum rated horsepower. During such operation, the engine shall be run at the exhaust back pressure specified in § 85.123(c) and the air inlet restriction specified in § 85.123(d) except that the tolerances shall be ±0.5 inches of Hg. and ±3 inches of water respectively. Exhaust smoke tests shall be conducted at zero and 125 hours of operation.

(b) Durability data engines: Each engine shall be operated on a dynamometer for 1,000 hours with the dynamometer and engine adjusted so that the engine is operating at 95–100 percent of rated speed and at least 95 percent of maximum rated horsepower. During such operation, the engine shall be run at the exhaust back pressure specified in § 85.123(c) and the air inlet restriction specified in § 85.123(d) except that the tolerances shall be ±0.5 inches of Hg. and ±3 inches of water respectively. Exhaust smoke measurements shall be made at zero hours and at each 125 hours of operation. All results except the zero hour results shall be used to establish the deterioration factors (see § 85.133).

(c) All tests required by this subpart to be conducted after 125 hours of dynamometer operation or at any multiple of 125 hours may be conducted at any accumulated hours within 8 hours of 125 hours or the appropriate multiple of 125 hours, respectively.

(d) The results of each emission test shall be supplied to the Secretary immediately after the test. In addition, all test data shall be compiled and provided to the Secretary in accordance with § 85.53.

(e) Whenever the manufacturer proposes to operate and test an engine which may be used for emission or durability data, he shall provide the zero hour test data to the Secretary and make the engine available for such testing under § 85.54 as the Secretary may require before beginning to accumulate hours on the engine. Failure to comply with this requirement shall invalidate all test data submitted for this engine.

(f) Once a manufacturer begins to operate an emission data or durability data engine, as indicated by compliance with paragraph (e) of this section, he shall continue to run the engine to 125 hours or 1,000 hours, respectively, and the data from the engine shall be used in the calculations under § 85.133. Discontinuation of an engine shall be allowed only with the prior written consent of the Secretary.

§ 85.133 Compliance with emission standards.

(a) The emission standards in the regulations in this part apply to the lifetime emission of engines in public use. Prior to certification, lifetime emissions can be obtained by projection of test data to lifetime normal service. Lifetime normal service or its equivalent is taken to be 2,000 hours of prescribed dynamometer operation.

(b) It is expected that the opacity of exhaust emissions will change with use of the engine. It is assumed that the emission level corresponding to 1,000 hours of prescribed dynamometer operation is the average emission of an engine over its lifetime.

(c) The procedure for determining compliance with exhaust smoke emission standards in heavy duty diesel engines is as follows:

(1) Emission deterioration factors for the acceleration mode (designated as "A") and the lugging mode (designated as "B") shall be established separately for each engine-system combination.

(i) The applicable results to be used in determining the deterioration factors for each combination shall be:

(*a*) All emission data from the tests required under § 85.132(b), except the zero hour tests. This shall include the official test results, as determined in § 85.54, for all tests conducted on all durability engines of the combination selected under § 85.130(c) (including all engines elected to be operated by the manufacturer under § 85.130(c)(2)).

(*b*) All emission data from the tests conducted before and after the maintenance provided in § 85.131(a)(1)(i).

(ii) All applicable results shall be plotted as a function of the hours on the system, rounded to the nearest hour, and the best fit straight lines, fitted by the method of least squares, shall be drawn through these data points. The interpolated 125 and 1,000 hour points on this line must be within the standard provided in § 85.41 or the data shall not be used in calculation of a deterioration factor.

(iii) The deterioration factors will be calculated as follows:

A-percent opacity "a", interpolated to 1,000 hours, minus percent opacity "a," interpolated to 125 hours.

B-percent opacity "b", interpolated to 1,000 hours, minus percent opacity "b", interpolated to 125 hours.

(2) The "percent opacity" values to compare with the standards shall be the opacity values "a" and "b" for each emission data engine within an engine-system combination to which are added the respective factors "A" and "B" of subparagraph (1) of this paragraph for that engine-system combination: *Provided*, That if a deterioration factor as computed in subparagraph (1) of this paragraph is less than zero, that deterioration factor shall be zero for the purposes of this subparagraph.

(3) Every test engine of an engine family must comply with all applicable standards, as determined in subparagraph (2) of this paragraph, before any engine in that family will be certified.

APPENDIX B

NEW JERSEY SMOKE TEST PROCEDURES
(NEW JERSEY AIR POLLUTION CONTROL CODE, CHAPTER 14)

CHAPTER 14, AIR POLLUTION CONTROL CODE

SECTION 1 - DEFINITIONS

1.1 PERSON: Includes corporations, companies, associations, societies, firms, partnerships and joint stock companies as well as individuals, and shall also include all political subdivisions of this State or any agencies or instrumentalities thereof.

1.2 MOTOR VEHICLE: Includes all vehicles propelled otherwise than by muscular power, excepting such vehicles as run only upon rails or tracks.

1.3 AUTOBUS: Includes all motor vehicles used for the transportation of passengers for hire.

1.4 DIESEL-POWERED MOTOR VEHICLE: A self-propelled vehicle designed primarily for transporting persons or property on a public street or highway which is propelled by a compression ignition type of internal combustion engine; for purposes of this chapter passenger automobiles and motorcycles are excluded.

1.5 DIESEL-POWERED ENGINE: A mechanism for converting energy into mechanical force and motion by using a compression ignition type of internal combustion engine.

1.6 SMOKE: Small gasborne and airborne particles, exclusive of water vapor, arising from a process of combustion in sufficient number to be observable.

1.7 OPACITY: The property of a substance which renders it partially or wholly obstructive to the transmission of visible light expressed as the percentage to which the light is obstructed.

1.8 EXHAUST EMISSIONS: Substances emitted into the atmosphere from any opening downstream from the exhaust ports of a motor vehicle engine.

1.9 SMOKEMETER: A device constructed in such manner as to measure smoke opacity by light obstruction between a light source and photoelectric cell which will indicate the percent opacity of smoke at a point approximately four (4) inches from the engine exhaust outlet. The device shall be of design meeting "Specification for Diesel-Powered Vehicle Smokemeter" on file with the State Commissioner of Environmental Protection and approved for use in accordance with manufacturers' recommended procedures for calibration, mounting and maintenance.

1.10 OPERATING MODE: A procedure for operating a diesel-powered motor vehicle or a diesel-powered engine during measurement of smoke opacity in the exhaust emissions.

1.11 CHASSIS DYNAMOMETER: A device constructed in such a manner as to simulate highway driving conditions on a stationary motor vehicle.

1.12 RPM - Revolutions per minute

1.13 MPH - Miles per hour

SECTION 2 - PUBLIC HIGHWAY STANDARD

2.1 No person shall operate any diesel-powered motor vehicle or permit any diesel-powered motor vehicle which he owns to be operated upon the public highways of the State if the vehicle, when in motion, emits visible smoke in the exhaust emissions within the proximity of the exhaust outlet, for a period of more than five (5) seconds.

SECTION 3 - INSPECTION STANDARD

3.1 Any motor vehicle propelled by a diesel-powered engine which is subject to inspection at the premises or places of business of the owner or lessee by the Division of Motor Vehicles as a condition of compliance with said inspection, shall not emit smoke in the exhaust emissions in excess of the smoke opacity standards set forth in Table 1.

3.2 Any autobus propelled by a diesel-powered engine which is subject to inspection at the premises or places of business of the owner or lessee by the Public Utilities Commission as a condition of compliance with said inspection shall not emit smoke in the exhaust emissions in excess of the smoke opacity standard set forth in Table 2.

TABLE 1

VEHICLES SUBJECT TO INSPECTION BY THE DIVISION OF MOTOR VEHICLES

(Reference P.L. Title 39:8-10)

Type of Inspection	Operating Mode*	Smoke Opacity Standard
Self inspection authorized by Division of Motor Vehicles at the premises or places of business of the owner or lessee	(1) Vehicle driven on chassis dynamometer with simulated load by power absorption	20%
	-alternate-	
	(2) Vehicle driven in low gear with simulated load by braking action	20%

*PROCEDURES:

(1) VEHICLE DRIVEN ON CHASSIS DYNAMOMETER WITH SIMULATED LOAD BY POWER ABSORPTION - with smokemeter firmly positioned on the exhaust outlet and vehicle positioned on the chassis dynamometer proceed with the following steps:

STEP 1

With vehicle on a chassis dynamometer under no power absorption, select a gear ratio which will produce a maximum vehicle speed of 45-60 MPH at governed engine RPM.

STEP 2

With engine running at governed engine RPM, apply power absorption load to the dynamometer until such loading reduces the engine RPM to 80 per cent of the governed speed, the peak smoke opacity measured over a period of 5 to 10 seconds with the engine under such loading shall be the smoke opacity.

*PROCEDURES:

(2) VEHICLE DRIVEN IN LOW GEAR WITH SIMULATED LOAD BY BRAKING ACTION - with smokemeter firmly positioned on the exhaust outlet, proceed with the following steps:

STEP 1

Select a gear ratio which will produce a maximum speed of 10-15 MPH, at governed engine RPM, drive vehicle at 10-15 MPH at governed engine RPM.

STEP 2

Load the engine by applying brakes until engine RPM is lugged down to 80 per cent of the governed engine RPM, the peak smoke opacity measured over a period of 5-10 seconds with the engine under such brake loading shall be the smoke opacity.

NOTE:

(a) All measurements are to be made after engines have been run a sufficient period of time to be at normal operating temperature.

(b) Separate measurements shall be made on each exhaust outlet on vehicles equipped with dual exhaust outlets.

TABLE 2

INSPECTION STANDARDS

VEHICLES SUBJECT TO INSPECTION BY THE PUBLIC UTILITIES COMMISSION

(Reference P.L. Title 48: 40-2.1 and 2.1A, Title 48: 4-18)

Type of Inspection	Operating Mode*	Smoke Opacity Standard
Inspection of Public Utilities Commission at the premises or places of business of the owner or lessee	Autobus driven with rapid acceleration	40%

*PROCEDURE

STEP 1

With smokemeter firmly positioned on exhaust outlet and transmission engaged, drive autobus by accelerating as rapidly as possible to approximately 20 MPH.

STEP 2

Release accelerator pedal and brake to full stop.

STEP 3

The peak smoke opacity measured during the acceleration to 20 MPH shall be the smoke opacity.

NOTE:

(a) All measurements are to be made after engines have been a sufficient period of time to be at normal operating temperature.

(b) Separate measurements shall be made on each exhaust outlet on vehicles equipped with dual and separated exhaust outlets.

(c) A single, combined measurement shall be made on the exhaust outlets on vehicles equipped with dual, adjacent exhaust outlets.

APPENDIX C

Information and Operating Instructions For PHS End-of-Line and Inline Smokemeters

June 1970

"Revised Preliminary Operating Instructions for Use of the U.S. Public Health Service Full-Flow, Light-Extinction Smokemeter"

This revised preliminary procedure is offered to acquaint the user with the PHS smokemeter and its basic operation. For details regarding the design principle, method of construction, specifications, drawings, etc., please refer to the letter from the Public Health Service to interested industry members from Howe Hopkins, NAPCA, dated January 4, 1968, and revised February 19, 1968. Additional changes requested by NAPCA in wiring and circuitry have required the February 1968 instructions to be revised.

General

The PHS smokemeter consists of two items, an optical light source photo cell assembly which is mounted on an exhaust stack, and a remote readout box containing air purge controls and a meter for indication of percent light opacity External requirements for use of this smokemeter are a stable minimum 6.5 volt DC, 2.75 amp power supply, and an approximate 2 SCFM of 60-120 psi shop air. A 0-10 mv output is available from the smokemeter readout box suitable for use with a 0-10mv null balance potentiometric type strip chart recorder, if desired.

Mounting of the Smokemeter

To measure smoke from a 4" OD stack, the usual procedure is to locate the 10" OD aluminum ring on which the collimating tubes are mounted such that the smoke plume is contained within, yet completely fills, the ring.

To Place Smokemeter in Service

1. Mount optical device on pipe and connect air hose and interconnect cable to readout box. Connect shop air to air inlet on readout box. Adjust pressure regulator to give 2 SCFM air purge to the optical device (Calibration curve supplied on inside lid of readout box).

2. Connect DC power supply using 2 conductor cable provided (Alligator clips are provided for use with cell battery, if desired). Red (positive) clip should be connected to the positive pole of power source.

FOR READOUT BOXES EQUIPPED WITH API, 100 - 0% OPACITY METERS

3. Turn power switch to "on" and meter-recorder switch to "meter". Turn three-position switch to "lamp volts". Remove cover from light bulb and, using a sensitive voltmeter connected across the bulb terminals, adjust external power supply to give 6 volts at light bulb with bulb in circuit and burning. It is assumed that the external power supply is adjustable or can be so modified. Next, remove panel board and adjust small potentiometer (black in color, Bourns No. 3007P)

located on underside of panel to read 40% (6 volts) on the remote box meter. The microammeter used to read percent transmittance is now in the circuit as a DC voltmeter and zero opacity is equivalent to 10 volts. This procedure results in 6 volts DC at the bulb and the instrument meter is calibrated in the circuit to reflect the voltage applied at the bulb. Only a minor trim adjustment should be necessary as the setting should be fairly stable during shipment and day to day use.

4. Turn three-position switch to "meter" and adjust "calibration" pot (10 turn located below meter in center of panel) to full scale zero percent light opacity. (Mechanical zero (100%) should be checked and adjusted prior to this step as meter may change static zero due to shipment).

5. If measurement via meter indicator is desired, the smokemeter is ready for use and the engine exhaust or other source of smoke can now be passed through the optical device.

6. If it is desired to continuously record the output via a strip chart recorder, connect external 0-10 mv to a suitable precalibrated null balance recorder. Flip meter-recorder toggle switch to "recorder" position. Zero recorder by depressing red button to the left of the calibration dial using zero adjust on recorder. Should recorder zero require adjustment, the recorder should be recalibrated with a laboratory millivoltage source. Next, adjust to 10mv full scale recorder indication using the 10 turn "rec. adj." potentiometer. The smokemeter is now ready for operation.

To Take Smokemeter Out of Service

1. Turn three-position switch to "off".
2. Turn power switch to "of".
3. After engine is shut down, disconnect or turn "off" air supply.
4. Place "shorting connector" provided on interconnect lead if disconnected from remote box.

Maintenance

Due to the simplicity of design, lack of sophisticated electronics, etc., this smokemeter, if handled properly, should be relatively trouble-free. Do not handle optical unit by the collimating tubes. Difficulties in drift or change in baseline are generally caused by one of two things:

1. Dirty or increasingly dirty lens and photo cell.
2. An unstable DC power supply such as a wet cell battery. (A wet battery, if used over an extended period of time, will discharge sufficiently to result in low readings. A trickle charger or similar battery boosting device or a suitable substitute power source is recommended.)

Supplied with the instrument is an extra GE No. 1630 light bulb and leads for simple replacement should the light bulb burn out. (Located under instrument panel).

It is recommended that periodic cleaning of the light source lens and photo cell be made. How often this will be necessary will depend on the usage of the instrument, the amount of smoke passed, etc. It is important to have the purge air on before starting engine or other source of smoke as this will greatly extend the cleanliness and reduce the amount of lens cleaning necessary. When replacing the light bulb in the light bulb socket, it should be noted that elongated holes are provided in the mounting flange to permit movement and adjustment of the light bulb position relative to the collimating tubes. Adjust the position of the light bulb so that the light beam is centered in the collimating tube on which the photo cell is mounted. This adjustment should permit ample light intensity to drive the meter indicator to 0 percent with reserve calibration adjustment. Should 0 percent light opacity be difficult to obtain under clear conditions, suspect either low voltage, dirty lens and photo cell, or incorrect positioning of the light bulb in the collimating tubes.

These instructions are provided in lieu of an official NAPCA publication and are subject to revision.

Operation and Maintenance of the PHS Inline Smokemeter

General

The PHS inline smokemeter consists of an optical unit containing the light source and photocell assemblies, which is mounted in the exhaust system, and a remote readout-control box containing purge air controls, a meter to indicate smoke opacity, and controls to zero and upscale the smokemeter during calibration. A 0-10mv output is available from the readout box for use of a strip chart recorder, if desired.

Smokemeter Power Supply

The same power supply and lamp voltage (6.0vDC) that are used for the end-of-line smokemeter are satisfactory for the inline instrument. A toggle switch has been added to the panel of the conventional read-out box to permit the normal ten mv output from the voltage divider. This switch deletes the 200 ohm and 750 ohm resistors from the voltage divider, as shown on the wiring diagram (p. C-8).

Smokemeter Purge Air

The usual air supply controlled through the regulator in the read-out box is connected to the stainless steel center body to purge the small sealed optical tubes. Set the pressure gage at 45 psig. This setting produces three SCFM of air, which is satisfactory. It is important to turn this purge air on before starting the engine and, since excessive heat may damage the Viton gaskets used to seal the small tubes at the glass lens, the purge should be left on for at least ten minutes after engine shut-down.

A separate air supply for the large collimating tubes is furnished, and includes a regulator, flow orifice, pressure gage, and water separator. This purge system is provided to cool the lamp and photocell and also to keep the collimating tubes clear of any smoke circulating in the vicinity of the smokemeter. The pressure should be set to about 29 psig for about two SCFM flow.

Calibrating the Inline Smokemeter

The inline instrument should be calibrated with the same two-in diameter neutral density filters that are furnished with the regular PHS smokemeter. Calibration is complicated somewhat by the instruments position in the exhaust system. One end of the smokemeter must be disconnected from the exhaust system and the filter held in the light beam passing through the pipe. The filter should be held at a right angle to the light beam. The pertinent calibration data for the inline smokemeter is given as follows:

CALIBRATION DATA FOR PROTOTYPE IN-LINE VERSION OF PHS SMOKEMETER
SERIAL NUMBER IL1002

Neutral Density Calibration Results

ND Filter Calibrated Opacity, %	Recorder Opacity, %
22.5	22.5
37.5	37.6
49.5	49.7
61.0	61.3
69.0	69.3
73.5	73.5
77.0	77.2
82.5	82.4
86.0	86.1
89.5	89.5

With the toggle switch in position "Increase Output to Recorder" and lamp burning at 6.0v DC, the following values should be observed:

(1) With ten-turn pot labeled "Recorder Adjust" set at 2.07, output to recorder is ten mv.

(2) With this pot at its maximum setting, recorder output is 12 mv.

(3) With ten-turn pot labeled "Calibrate" at its maximum setting, panel meter reading is 65%.

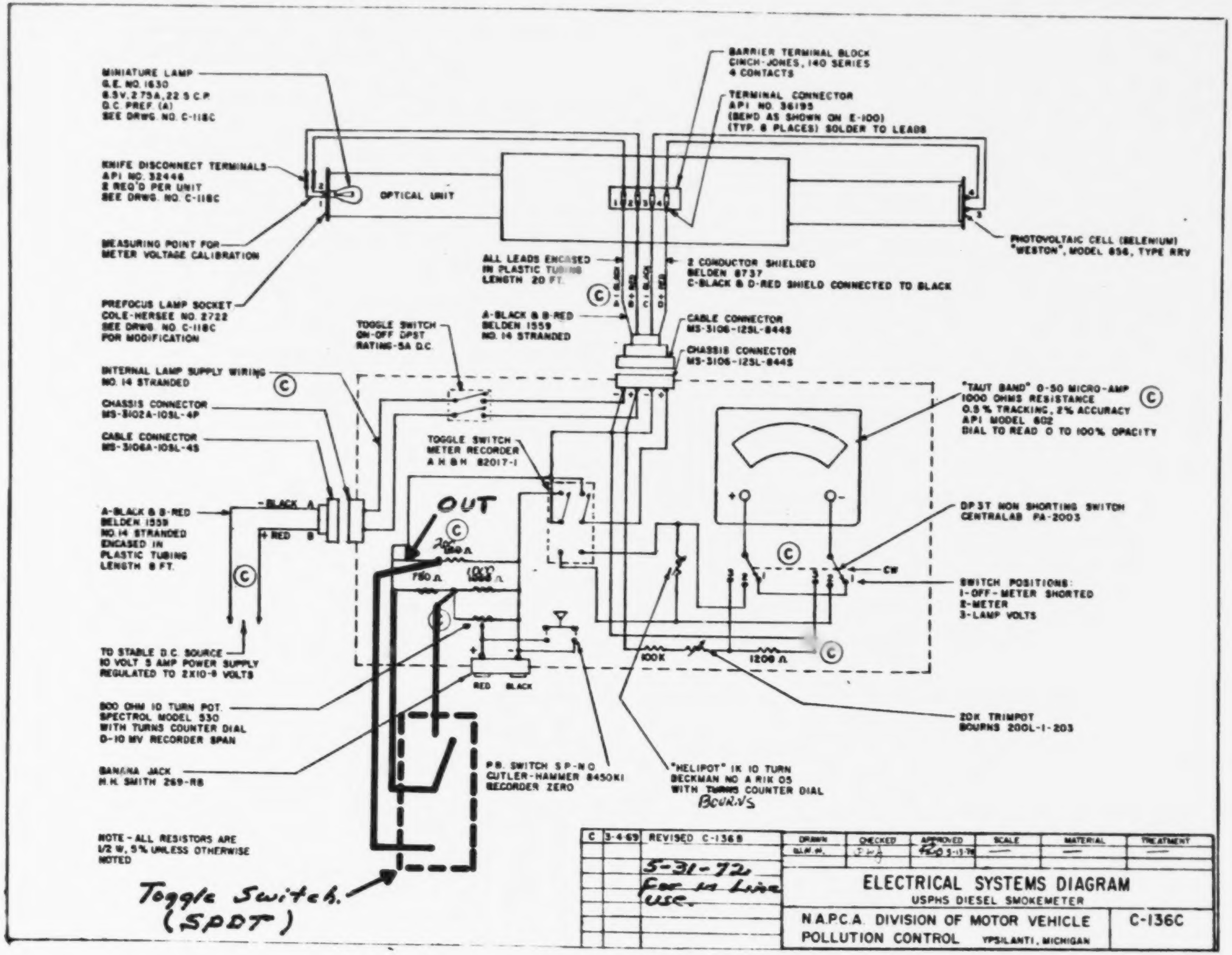
Several minutes should be allowed between engine shut-down and any attempt to zero the smokemeter. This wait will allow smoke in the pipe to dissipate and hence permit a true zero reading to be obtained.

Cleaning the Smokemeter

The glass lenses can be removed for cleaning by the following procedure. First, unbolt completely the mounting bracket which locates the ten-in diameter optical ring to the central stainless steel exhaust pipe. Or, alternatively, remove both large collimating tubes from the ring at the four-bolt flange. Either of these steps will allow access to the brass male-type threaded nut at the end of the small sealed tube. The lens and the Viton gaskets can then be removed from the tube. The lens is cleaned by wiping with a clean cloth, while the inside of the small tube can be cleaned by running a swab through it, much like cleaning a rifle bore.

Reassembling the Smokemeter

Replace the gaskets and lens in the end of the small tube, making sure the gaskets fit squarely against the lens. Tighten the brass nut just enough to achieve a snug fit. Do not overtighten the nut, as the lenses are easily cracked by excessive pressure. Reassemble the large collimating tubes and their mounting bracket onto the central exhaust pipe. With the lamp burning and a ten mv-span recorder connected to the output, adjust the position of the mounting bracket on the pipe so that a minimum of ten mv output is obtained with some gain adjustment remaining on the ten-turn pot labeled "Recorder Adjust".


MINIATURE LAMP
G.E. NO. 1630
6.5V, 2.75A, 22.5 C.P.
D.C. PREF. (A)
SEE DRWG. NO. C-118C
KNIFE DISCONNECT TERMINALS
API NO. 32446
2 REQ'D PER UNIT
SEE DRWG. NO. C-118C
MEASURING POINT FOR METER VOLTAGE CALIBRATION
PREFOCUS LAMP SOCKET
COLE-HERSEE NO. 2722
SEE DRWG. NO. C-118C
FOR MODIFICATION
OPTICAL UNIT
BARRIER TERMINAL BLOCK
CINCH-JONES, 140 SERIES
4 CONTACTS
TERMINAL CONNECTOR
API NO. 36195
(BEND AS SHOWN ON E-100)
(TYP. 8 PLACES) SOLDER TO LEADS
PHOTOVOLTAIC CELL (SELENIUM)
"WESTON", MODEL 856, TYPE RRV
ALL LEADS ENCASED IN PLASTIC TUBING LENGTH 20 FT.
2 CONDUCTOR SHIELDED
BELDEN 8737
C-BLACK & D-RED SHIELD CONNECTED TO BLACK
A-BLACK & B-RED
BELDEN 1559
NO. 14 STRANDED
CABLE CONNECTOR
MS-3106-12SL-844S
CHASSIS CONNECTOR
MS-3106-12SL-844S
TOGGLE SWITCH
ON-OFF DPST
RATING-5A D.C.
INTERNAL LAMP SUPPLY WIRING
NO. 14 STRANDED
CHASSIS CONNECTOR
MS-3102A-10SL-4P
CABLE CONNECTOR
MS-3106A-10SL-4S
TOGGLE SWITCH
METER RECORDER
A H & H 82017-1
A-BLACK & B-RED
BELDEN 1559
NO. 14 STRANDED
ENCASED IN
PLASTIC TUBING
LENGTH 8 FT.
-BLACK A
+RED B
OUT
200 Ω
750 Ω
1000 Ω
RED
BLACK
TO STABLE D.C. SOURCE
10 VOLT 3 AMP POWER SUPPLY
REGULATED TO 2X10-6 VOLTS
800 OHM 10 TURN POT.
SPECTROL MODEL 530
WITH TURNS COUNTER DIAL
0-10 MV RECORDER SPAN
BANANA JACK
H.H. SMITH 269-R8
P.B. SWITCH S.P.-N.O.
CUTLER-HAMMER 8450K1
RECORDER ZERO
"HELIPOT" 1K 10 TURN
BECKMAN NO. A RIK 05
WITH ~~TURNS~~ COUNTER DIAL
BOURNS
100K
1200 Ω
20K TRIMPOT
BOURNS 200L-1-203
"TAUT BAND" 0-50 MICRO-AMP
1000 OHMS RESISTANCE
0.5% TRACKING, 2% ACCURACY
API MODEL 602
DIAL TO READ 0 TO 100% OPACITY
DP3T NON SHORTING SWITCH
CENTRALAB PA-2003
CW
SWITCH POSITIONS:
1-OFF-METER SHORTED
2-METER
3-LAMP VOLTS
NOTE - ALL RESISTORS ARE 1/2 W, 5% UNLESS OTHERWISE NOTED
Toggle Switch. (SPDT)
C 3-4-69 REVISED C-136B
5-31-72 For in Line use.
DRAWN
CHECKED
APPROVED
SCALE
MATERIAL
TREATMENT
5-13-70
ELECTRICAL SYSTEMS DIAGRAM
USPHS DIESEL SMOKEMETER
N.A.P.C.A. DIVISION OF MOTOR VEHICLE POLLUTION CONTROL YPSILANTI, MICHIGAN
C-136C

APPENDIX D

SMOKE TRACE EVALUATION SHEETS FOR FEDERAL SMOKE TESTS WITH PHS END-OF-LINE AND INLINE SMOKEMETERS

SMOKE TRACE EVALUATION SHEET

Smokemeter: End-of-Line

Date: March 7, 1972

Engine: Cummins NHC-250

Truck No: 274

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	9.0	1	17.5	1	12.0
2	14.0	2	21.0	2	15.5
3	14.0	3	25.0	3	16.0
4	19.0	4	27.5	4	18.7
5	24.0	5	32.5	5	20.0
6	23.5	6	35.5	6	18.0
7	23.0	7	30.0	7	22.0
8	24.5	8	28.0	8	20.0
9	27.0	9	29.0	9	20.0
10	27.0	10	30.0	10	21.5
11	28.5	11	34.0	11	23.5
12	27.0	12	33.0	12	25.0
13	24.0	13	33.0	13	28.0
14	26.3	14	32.5	14	27.0
15	24.0	15	34.0	15	25.0
Total Smoke %	334.8		442.5		312.2

Factor (a) = $\frac{1089.5}{45}$ = 24.2%

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	30.0	1	32.0	1	35.0
2	31.3	2	31.5	2	37.0
3	31.0	3	31.0	3	35.0
4	33.2	4	34.0	4	36.0
5	33.0	5	32.0	5	36.0
Total Smoke %	158.5		160.5		179.0

Factor (b) = $\frac{495.0}{15}$ = 33.2%

Comments: 144

D-3.

SMOKE TRACE EVALUATION SHEET

Smokemeter: Inline

Date: March 7, 1972

Engine: Cummins NHC-250

Truck No: 274

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	9.5	1	13.0	1	13.5
2	15.3	2	18.0	2	19.0
3	17.0	3	22.0	3	16.0
4	22.1	4	25.0	4	20.0
5	25.0	5	28.0	5	20.0
6	22.5	6	27.5	6	20.0
7	24.5	7	30.0	7	21.5
8	25.3	8	31.0	8	24.0
9	225	9	28.8	9	24.5
10	250	10	30.0	10	24.0
11	26.0	11	29.0	11	26.0
12	22.0	12	31.5	12	28.5
13	21.9	13	30.0	13	28.0
14	26.3	14	30.5	14	29.0
5	26.0	15	30.0	15	28.0

Total Smoke % 330.9 404.3 342.0

Factor (a) = $\frac{1077.2}{45}$ = 23.9%

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	30.0	1	31.0	1	30.0
2	29.0	2	33.0	2	30.0
3	30.0	3	35.0	3	29.5
4	30.5	4	34.0	4	29.5
5	28.0	5	37.0	5	35.0

Total Smoke % 147.5 168.0 154.0

Factor (b) = $\frac{469.5}{15}$ = 31.3%

Comments: 145

SMOKE TRACE EVALUATION SHEET

Smokemeter: End-of-Line

Date: March 17, 1972

Engine: Cummins V-903

Truck No: 972

Acceleration s

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	18.0	1	7.0	1	3.0
2	21.0	2	8.5	2	7.5
3	21.0	3	11.8	3	10.0
4	17.0	4	14.5	4	10.0
5	18.3	5	15.0	5	9.5
6	30.0	6	19.2	6	10.0
7	29.8	7	27.5	7	11.0
8	27.5	8	33.0	8	12.5
9	20.0	9	27.2	9	16.0
10	13.5	10	27.0	10	20.5
11	15.0	11	24.0	11	24.0
12	17.0	12	23.5	12	22.5
13	15.0	13	22.5	13	19.8
14	19.0	14	23.0	14	20.0
15	20.0	15	24.0	15	18.5

Total Smoke % 302.1 | 307.7 | 214.8

Factor (a) = $\frac{824.6}{45}$ = 18.3 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	23.5	1	20.0	1	24.5
2	22.0	2	21.0	2	22.0
[illegible]	21.5	3	20.8	3	22.5
[illegible]	21.5	4	20.5	4	22.2
[illegible]	22.0	5	20.3	5	21.0

Total Smoke % 110.5 | 102.6 | 112.2

Factor (b) = $\frac{325.3}{15}$ = 21.7 %

Comments: 146

SMOKE TRACE EVALUATION SHEET

Smokemeter: Inline

Date: March 17, 1972

Engine: Cummins V-903

Truck No: 972

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	11.0	1	5.0	1	3.0
2	16.0	2	6.0	2	6.0
3	17.0	3	7.5	3	7.6
4	15.0	4	8.5	4	7.5
5	14.8	5	13.0	5	8.0
6	19.0	6	17.5	6	8.5
7	26.0	7	22.0	7	9.5
8	25.9	8	25.0	8	12.0
9	20.0	9	21.5	9	15.5
10	15.0	10	19.5	10	20.0
11	13.0	11	19.0	11	20.5
12	14.8	12	20.0	12	18.0
13	15.5	13	20.2	13	17.3
14	19.0	14	18.5	14	17.0
15	17.0	15	15.0	15	17.3

Total Smoke % 259.0 238.2 187.7

Factor (a) = $\frac{684.9}{45}$ = 15.2 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	18.0	1	18.3	1	17.5
2	17.9	2	18.0	2	16.0
3	18.5	3	18.0	3	16.0
4	17.5	4	17.5	4	16.3
5	18.2	5	17.5	5	16.4

Total Smoke % 90.1 89.3 82.2

Factor (b) = $\frac{261.6}{15}$ = 17.4 %

Comments: 147

SMOKE TRACE EVALUATION SHEET

Smokemeter: End-of-Line

Date: March 24, 1972

Engine: Mack ENDT 673B

Truck No: 60124

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	14.8	1	14.0	1	15.0
2	19.5	2	21.8	2	23.0
3	18.5	3	19.8	3	21.0
4	16.2	4	17.5	4	20.3
5	15.3	5	19.0	5	16.5
6	15.0	6	17.5	6	17.5
7	14.5	7	17.0	7	15.5
8	15.2	8	18.0	8	15.5
9	15.0	9	15.0	9	17.3
10	12.0	10	14.8	10	13.0
11	11.5	11	12.0	11	11.5
12	11.0	12	12.5	12	10.0
13	10.5	13	11.5	13	9.8
14	10.5	14	9.0	14	8.5
15	10.0	15	11.3	15	10.3

Total Smoke % 209.5 230.7 224.7

Factor (a) = $\frac{6649}{45}$ = 14.8 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	9.0	1	9.5	1	6.0
2	8.8	2	9.0	2	6.2
3	9.2	3	9.0	3	7.0
4	8.0	4	9.0	4	7.3
5	9.5	5	9.5	5	7.0

Total Smoke % 44.5 46.0 33.5

Factor (b) = $\frac{1240}{15}$ = 8.3 %

Comments:

SMOKE TRACE EVALUATION SHEET

Smokemeter: Inline

Date: March 24, 1972

Engine: Mack ENDT 673B

Truck No: 60124

Accelerations

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	14.5	1	12.0	1	14.0
2	16.5	2	17.0	2	15.5
3	14.8	3	15.0	3	14.5
4	13.0	4	14.0	4	12.5
5	11 5	5	14.0	5	12.5
6	11.5	6	14.0	6	13.5
7	12.3	7	13.9	7	11.0
8	13.0	8	14.0	8	13.0
9	11.8	9	13.0	9	12.0
10	10.0	10	11.0	10	9.5
	9.8	11	10.0	11	8.5
12	8.5	12	10.0	12	8.0
13	9.0	13	9.8	13	8.0
14	7.0	14	7.5	14	6.5
15	7.5	15	7.5	15	6.7

Total Smoke % 171.0 182.7 165.7

Factor (a) = $\frac{519.4}{45}$ = 11.5 %

Lugging

First Sequence		Second Sequence		Third Sequence	
Interval No.	Smoke %	Interval No.	Smoke %	Interval No.	Smoke %
1	7.0	1	6.3	1	5.2
2	8.0	2	6.5	2	5.3
3	6.5	3	7.0	3	5.2
4	6.5	4	6.2	4	5.4
5	7.0	5	7.0	5	5.0

Total Smoke % 35.0 33.0 26.1

Factor (b) = $\frac{94.1}{15}$ = 6.3%

Comments: 149